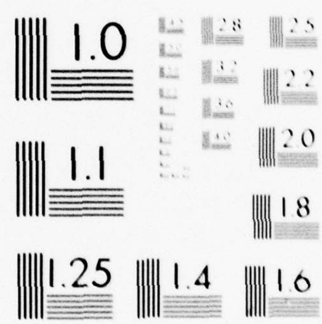
AD-A070 775 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
SYSTEMS INTEGRATION: RNAV AND THE UPGRADED THIRD GENERATION SYS--ETC(U)
DEC 76 E H BOLZ, R W SCOTT, A R STEPHENSEN DOT-FA72WA-3098

UNCLASSIFIED FAA-RD-77-22 NL

AD
A070775



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Report No. FAA-RD-77-22

SYSTEMS INTEGRATION: RNAV AND THE UPGRADED THIRD GENERATION SYSTEM

E. H. BOLZ
R.W. SCOTT
A.R. STEPHENSON
W. HEINE

DECEMBER 1976
FINAL REPORT

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No. FAA-RD-77-22	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SYSTEMS INTEGRATION: RNAV AND THE UPGRADED THIRD GENERATION SYSTEM		5. Report Date December 1976
		6. Performing Organization Code
		8. Performing Organization Report No.
7. Author(s) E.H. Bolz, R.W. Scott, A.R. Stephensen, W. Heine		
9. Performing Organization Name and Address Systems Control, Inc.(Vt) 1801 Page Mill Road Palo Alto, California 94304		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DOT-FA72WA-3098
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D. C. 20591		13. Type of Report and Period Covered Final Report July 1975 through December 1976
		14. Sponsoring Agency Code ARD-333

15. Supplementary Notes
Report was prepared by Champlain Technology Industries, Division of Systems Control, Inc. (Vt), a subsidiary of Systems Control, Inc., Palo Alto, Calif. 94304

16. Abstract This document presents the results of an analysis of the features of the Upgraded Third Generation ATC System in a program of evaluation of the impact of the implementation of Area Navigation on the other features of the UG3RD System. This analysis includes evaluations of the impact of RNAV on the performance and costs of these UG3RD features and, in turn, their impact on the performance, costs and benefits attendant to the implementation of RNAV.

As a part of this study the UG3RD System has been examined from the systems integration point of view. One result of the study is the establishment of the effects which RNAV could have on UG3RD feature implementation schedule tradeoffs and interactions. These judgements were based upon a study of the problems of the existing ATC system, and the capabilities of each UG3RD feature, including RNAV, for solving each of these problems.

Earlier studies of RNAV implementation costs and benefits have been reviewed and any areas where UG3RD implementation plans would affect these cost/benefit figures have been identified, and the earlier figures recalculated. Overall RNAV implementation costs and benefits (airline, general aviation, ATC system and airline passenger) are projected annually to the year 2000. These annual figures have been discounted to present value totals (1976), according to guidelines issued by the Office of Management and Budget, and the resulting benefit/cost ratios of RNAV are presented herein.

17. Key Words	18. Distribution Statement
Air Navigation, Area Navigation, Economics, Upgraded Third Generation ATC System, Air Traffic Control, Airline Operations, Cost/Benefit Studies	Document is available to the public Through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	224	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

19 18 6 10 11 12 225p. 15 9

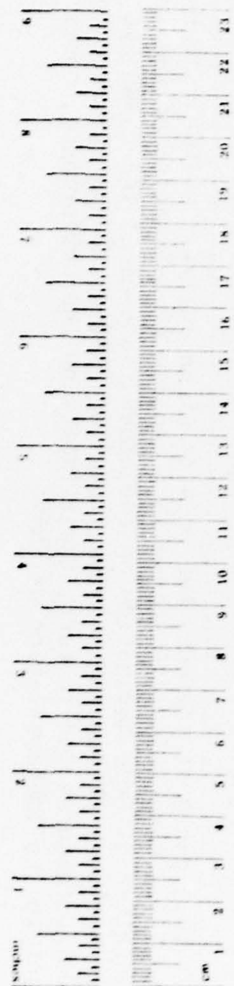
410 102

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

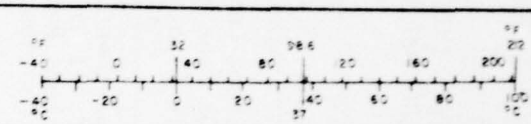
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The Systems Research and Development Service of the Federal Aviation Administration has undertaken a program to assess the technical and economic impact of Area Navigation on the ATC System and the users of the National Airspace System. This work was performed under the RNAV Technical Support Contract to Systems Control, Inc. (Vt), Contract No. DOT-FA72WA-3098, Task Order No. 013. The work was performed by the Champlain Technology Industries (CTI) and Aeronautical and Marine Systems (A&M) Divisions of Systems Control, Inc. (Vt).

The FAA Technical Monitor for this work was D. M. Brandewie and the Technical Support Program Manager was D. W. Richardson of Systems Control, Inc. (Vt). The Project Manager and principal author of this document was E. H. Bolz of Champlain Technology Industries, Division of Systems Control, Inc. (Vt).

This document is a final report containing the results of studies of the interactions of RNAV and the other features of the Upgraded Third Generation ATC System.

The following members of the technical staff of the CTI and A&M Divisions of Systems Control, Inc. (Vt) contributed to the conduct of this study:

E. H. Bolz (CTI)	Project management; study methodologies; cost/benefit analyses; analyses of DABS, IPC, Upgraded Automation, and ASTC interactions
R. W. Scott (CTI) W. Heine (A&M)	Analyses of MLS and WVAS interactions
A. R. Stephenson (A&M)	Analyses of FSS interactions

TABLE OF CONTENTS

PRECEDING PAGE BLANK

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF TABLES

(continued)

1.0 EXECUTIVE SUMMARY AND CONCLUSIONS

1.1 INTRODUCTION

This report contains detailed analyses of the interactions to be expected between Area Navigation (RNAV), which is an Upgraded Third Generation System program, and the remaining programs of the Upgraded Third Generation ATC System (UG3RD). These are to include identification of RNAV effects on those programs, the effects of those programs on RNAV, and the overall impact which RNAV will have on the functioning of the UG3RD ATC system. As a result, this study has included a detailed investigation of each of the domestic UG3RD system programs.

The improvements which comprise the UG3RD ATC system are designed to alleviate the several operational and economic limitations associated with the present Third Generation ATC System, both as it presently functions and as it would be expected to function as traffic grows over the next decade. It should be emphasized that the operational and economic problems affect both the users of the ATC system facilities and the ATC system itself. Other than to improve the margin of safety, the primary motivations for ATC improvements are <u>economic</u>:

- For the aircraft operator the motivations are to improve routing efficiency, reduce delays and improve operational reliability
- For the ATC system the motivations are to reduce operating costs-per-service rendered through enhancement of employee productivity

The following list summarizes the limitations of the existing ATC system as discussed in detail in Reference 52:

- Manual routine control-decision-making process
- Usage of voice communications for routine control instructions
- Limited ATCRBS surveillance radar accuracy and target reliability
- High airborne and ground delays due to terminal capacity limitations (wake vortex problem, visibility limitations, runway separation requirements, noise abatement constraints)
- Airborne and ground delays due to surface traffic control visibility limitations
- Severe operational and economic constraints on further Category I and II ILS deployment
- Inefficient flight services provision capability
- Continuing accidents, including midair collisions

These problems will be aggravated as traffic density increases. In response to these problems, and as a result of the recommendations of the Air Traffic Control Advisory Committee [13], the FAA has embarked on implementation of the following list of measures, which comprise the UG3RD system [52]:

- Discrete Address Beacon System -- to overcome the limitations of ATCRBS system
- Intermittent Positive Control -- an automated VFR/IFR separation assurance system
- Flight Service System Modernization -- including automation to improve productivity
- Upgraded ATC Automation -- to enhance safety and improve controller productivity

- Microwave Landing System -- to overcome the operational and cost limitations of ILS
- Area Navigation -- to improve routing efficiency and facilitate terminal operations
- Airport Surface Traffic Control -- to improve surveillance sensors and automate control functions
- Wake Vortex Avoidance System -- to allow closer in-trail separations under normal conditions
- Aerosate -- to improve oceanic communications capability

While these features form a complementary set of improvements, they are in varying stages of development and so will be implemented over a wide time span. Also, individual features may undergo change as they are developed and refined.

The remainder of this Executive Summary introduces RNAV functions, summarizes overall RNAV costs and benefits, reviews the effects which RNAV has been found to have on the overall UG3RD program, and presents the conclusions of this study.

1.2 APPLICATION OF RNAV TECHNIQUES TO THE UG3RD ENVIRONMENT

The basic capability of Area Navigation is to provide course guidance along arbitrary, pre-defined routes without constraints such as flying toward or over navigation stations, etc. The classic benefits attributed to RNAV are that (1) it can provide more direct routings from one airport to another since it operates with fewer constraints, and (2) it can improve the efficiency of terminal procedures by virtue of the fact that radar vector procedures may be supplanted by published RNAV arrival and departure routes, which would be self-navigated. The end result is more efficient operations and reduced ATC controller workload. Recent studies [6,8,15,37] have shown that there are many other benefits as well. Costs of avionics procurement have also been estimated. These costs and benefits are projected over a twenty-five year period in Section 1.3. The present section is oriented towards showing the effects of RNAV in an operational sense on cockpit and ATC procedures, and introducing the ways RNAV will interact with the other UG3RD programs.

RNAV provides the ability to program an arbitrary route. This can range in complexity from specifying a single waypoint over an airport and flying to it, all the way to pre-programming a departure route, the enroute phase, a terminal arrival route and an RNAV instrument approach procedure. This freedom and diversity brings with it a price which must be paid in terms of avionics cost, cockpit workload and data input blunder potential. RNAV operational problems and flight crew performance are examined in great detail in Reference 31. These problems interact, in that higher avionics cost brings lower cockpit workload, etc., and so the system can be matched to the requirement and to the expected economic payoff (costs versus benefits are detailed in Reference 8). User benefits are more than just those associated with flying shorter routes, as will become evident later.

To the ATC system, RNAV, on the surface, appears to complicate matters since new route structures will overlay existing routes (in the high altitude environment the existing structure would eventually be eliminated), and a "mix" of RNAV and conventional traffic will have to be tolerated. However, RNAV provides the potential for significant reductions in ATC controller workload, particularly in the terminal environment through the substitution of self-navigated procedures for

radar vector procedures, thereby reducing that aspect of the radar controllers' workload associated with providing navigational guidance. These overall benefits are reviewed in Section 1.3; however, it is of interest here to introduce other ways in which RNAV will interact with the operations of the ATC system.

In the enroute environment, several advantages may be obtained in addition to shorter routes. First of all, a well-ordered route structure, designed to reduce conflict points and ease controller workload, may be designed. This particularly applies to the high altitude environment where RNAV will probably become the exclusive navigation technique. Such a structure can contain alternate routings for major traffic flows in order that ambient wind conditions may be used to advantage. The preplanned direct (or arbitrary) route concept will allow users greater flexibility, although initially it may make the controller's job more complex. As automation is eventually expanded to relieve much of the controller burden, direct routes may be used to even greater advantage.

RNAV provides the controller with added tactical control options (parallel offset and direct-to-next-waypoint procedures) which may be used for airspace conflict resolution purposes. The parallel offset (which would be most popular) is easier for the controller than radar vectors since the surveillance requirement and message counts are reduced. The offset is better than an altitude reclearance for the aircraft operator since the latter usually means operating at a non-optimum altitude.

The primary applications of RNAV to the terminal area are that it (1) allows airspace to be allocated to the various arrival and departure routings more efficiently, and (2) promotes self-navigation of the routes, therefore reducing controller workload by a considerable extent. In addition, the terminal controller's set of control options is further enhanced by such procedures as the delay fan and base-leg extension techniques, as well as the parallel offset and direct-to procedures. One of the advantages of the reduction to workload, besides the eventual impact on staffing requirements, is that the controllers are free to more carefully sequence the arrival traffic, resulting in improved capacity and reduced delays [37].

The usage of RNAV terminal routes also allows special routes to be designated to satellite airports in major hub areas. This reduces workload and may guarantee conflict-free paths to these minor airports. RNAV can also be used for defining IFR noise-abatement routes. These would avoid noise sensitive areas and would be designed to intercept the ILS (or narrow-beam MLS) approach course. Departure noise-abatement routes can also be implemented.

RNAV capability may also be used for conducting non-precision instrument approach procedures. Primary candidates for RNAV procedures are non-ILS runways at major airports, particularly when they are used extensively for GA and STOL operations, and primary runways at the many smaller airports which do not have ILS capacity.

Many of the above benefits, as well as costs, have been quantified, the results of which are presented in the following section.

1.3 OVERALL RNAV BENEFITS AND COSTS

This section summarizes the results of a detailed analysis of RNAV costs and benefits projected over the period of years from the present to the year 2000. The intent of this study, which is described in Section 4 in detail, is to provide the basis for making educated decisions regarding the implementation of area navigation routes and procedures. An important factor in these decisions is the ratio of benefits to costs. In order to properly compensate for the passage of time encountered between the points where system implementation costs are expended and benefits are realized, overall costs and benefits must be presented in terms of their present (discounted) value. Guidelines for present value computation promulgated by the Office of Management and Budget have been used in this analysis [43].

In References 8 and 15, earlier studies of the costs and benefits of area navigation, detailed methodologies were developed for RNAV cost/benefit assessment. Reference 8 calculated projected benefits and costs for a typical implementation year (1984). However, these calculations have been revised and expanded in this report for three reasons:

1) To accommodate any changes in expected benefits or costs which have resulted from the present study of the interface of RNAV and the UG3RD.

2) To allow projections to be based upon the revised traffic and fleet projections data contained in the Baseline and Implementation Scenario [1].

3) To project, and to discount to present value, all benefits and costs from the present to the year 2000.

As a result, comprehensive and current assessments of overall RNAV benefits and costs, and present value benefit/cost ratios, may be made. In the following all air carrier benefits and costs are expressed as industry totals. Interested parties are referred to Section 4 which lists all benefits and costs by individual aircraft type category, which is of interest since the benefit/cost ratios can vary widely from type to type. Care should, however, be exercised in interpreting the benefit/cost results for individual aircraft categories. They express industry aggregate results over a fixed time period, and so express more conservative results than would be expected from benefit/cost analyses of individual aircraft in a given fleet, where the analyses would be carried over the aircraft lifetime.

1.3.1 RNAV User Costs

The costs to airspace users of RNAV equipage have been computed for the projected air carrier fleet and for those general aviation users most likely to equip. In general, air carrier aircraft were assumed to equip over three year periods, with wide-body aircraft starting in 1982 and narrow-bodies in 1983, although certain exceptions (two-engine, four-engine standard body) were made due to declining fleet size projections. RNAV equipage costs were taken to include equipment costs, spares inventory, one-time installation cost and crew training, plus annual maintenance and data base update costs. These

cost values are detailed in Section 4. A standard ARINC MK13 RNAV configuration was assumed for standard body aircraft, and more sophisticated and expensive units were presumed for the wide body aircraft. Dual (redundant) installations were presumed throughout, although dual installations are not required to obtain RNAV benefits. The summary airline equipage cost data are presented in Table 1.1. Costs from the present date are included since a few airlines are now equipping.

Table 1.1 Overall Air Carrier Equipage Costs, 1976-2000

/Note/ Dual (redundant Equipage Presumed

Units Installed	4442
Acquisition Costs Maintenance Costs	$1069M 367M
Present Value Total	$ 442M

It is difficult to predict which general aviation operators will be most likely to equip with RNAV capability. The dollar payoff is not nearly so large as in the airline case, but other operational benefits may be realized by GA operators. The relatively large number of GA RNAV units sold to date attests to their utility. The earlier cost/benefit study [8] quantifies dollar benefits of RNAV available to GA users; however, overall benefits to the GA segment have not been projected in this study since data sufficient to establish such a projection were not provided in Reference 1. To maintain an overall conservative estimate of RNAV benefit/cost ratio, the RNAV equipage costs applying to those GA aircraft most likely to be equipped have been computed and are included in this analysis. Those judged most likely to equip include all turbine aircraft, and all piston operators who are based at high or medium density hub airports. Single (non-redundant) equipage is presumed, with initial equipage starting in 1982 and continuing for four more years. Total acquisition, maintenance and present value costs are listed in Table 1.2.

Table 1.2 GA Equipage Costs, 1982-2000

/Note/ Single Equipage Presumed

	Turbine	Piston
Units Installed	29,345	7032
Acquisition Costs Maintenance Costs	$209.1M 86.4M	$29.5M 20.0M
Present Value Total	$ 76.4M	$18.8M

1.3.2 Air Carrier Benefits

In Section 4 detailed explanations are given describing the data sources, methods and assumptions used in projecting the benefits of RNAV to be realized by air carrier operators. All analyses have been conducted separately for each aircraft type category. Four RNAV benefit types have been studied: terminal area route and procedure benefits, enroute route length savings; VNAV descent procedure benefits, and 4D (time control) RNAV arrival benefits in an M&S environment.

Fleet size and operations data were taken from Reference 1, while benefits methodologies were taken from Reference 8. Also, the most recent (1975) CAB data concerning operating costs, fuel costs, stage lengths and departure rates was used (Reference 45). A scenario was developed describing the order and timing of the implementation of RNAV (and of 4D) in terminal areas. Overall benefits are stated in Table 1.3. Fuel and time benefits are stated directly. The cost value implications of these savings have been expressed in terms of maximum and minimum potential values. Stating two values was deemed necessary in order to account for the wide potential variation in future fuel prices, and to account for varying airline interpretations of the incremental cost of aircraft operating time. Specific values used for fuel and for time value for each aircraft category are listed and explained in Section 4. It should be mentioned that the higher of the two cost levels more closely represents probable future fuel prices and common airline costing policy.

Table 1.3 Overall Air Carrier RNAV Benefits, 1982-2000

	Terminal Procedures	Enroute	VNAV Descent	4D with M&S	TOTAL
Fuel Savings (gal)	3022M	3732M	843M	2774M	10,371M
Time Savings (hr)	1844K	1945K	592K	2355K	6,736K
TOTAL DOLLAR VALUE:					
Low Cost Assumption	$1627M	$1919M	$ 447M	$1823M	$ 5,816M
High Cost Assumption	2738M	3259M	726M	3118M	9,841M
1976 PRESENT VALUE:					
Low Cost Assumption	$ 371M	$ 425M	$ 105M	$ 401M	$ 1,302M
High Cost Assumption	622M	718M	170M	683M	2,193M

Present value costs and benefits having now been calculated, the airline benefit cost ratio may now be computed, as in Table 1.4. The resulting ratio, which ranges as high as 5.0, is far in excess of that required simply for justification and suggests a large potential payoff to the airlines. It should be mentioned that benefits prior to 1982 of several types will be available to equipped aircraft. These were left out of this analysis for purposes of simplification.

Table 1.4 Air Carrier Present Value Benefit/Cost Ratio, 1982-2000

Present Value Costs	$442M
PRESENT VALUE BENEFITS: Low Cost Assumption	$1302M 2193M
1976 B/C RATIO: Low Cost Assumption High Cost Assumption	 2.9 5.0

1.3.3 ATC Benefits and Costs

Section 4.2 discusses in detail the results summarized below. Major ATC benefit areas include the ability of RNAV to allow certain VORTAC stations to be removed from terminal areas, resulting in savings in maintenance costs, among others, and the ability of RNAV to reduce controller workload and increase productivity, resulting in ATC staffing reductions. Major ATC cost areas include certain improvements to the enroute VORTAC coverage network for RNAV route structure coverage, and the costs of implementing area navigation in the NAS. There are also other areas of minor cost or benefit impact, such as in the area of ATC automation costs (see Reference 8), which are not included in this analysis.

The terminal VOR maintenance savings benefit derives from the finding [8] that forty-eight stations could be removed from the fifty-four high and medium density terminal areas included in that analysis. While many types of savings could be realized from this removal, a conservative estimation was performed utilizing only the savings in maintenance cost expenditures. The total savings (1985-2000) amounts to $36M, or an $8M 1976 present value.

Terminal and enroute controller productivity improvements have been the subject of several studies [49,8], where it was found that the implementation of RNAV could result in 10% (terminal) and 14% (enroute) productivity improvements. A recent study of UG3RD feature productivity improvements and resulting staffing levels (Reference 50) was used as the basis of a projection of overall impact on staffing requirements. The results of these projections are stated in Table 1.5.

Table 1.5 RNAV Controller Productivity Benefits, 1982-2000

	Man-Years Saved	Dollars Saved	Present Value
26 Terminal Areas	1063	$ 26.4M	$ 8.0M
20 Enroute Centers	17,018	422.0M	210.7M

The major ATC cost areas studied were for enroute VORTAC improvements and RNAV implementation costs. Required VORTAC improvements include two new stations plus conversion of five existing low altitude stations to high altitude status, resulting in the following costs:

Capital Costs (1982)	$597K
Annual Maintenance	97K
1976 Present Value Total	841K

The RNAV implementation costs over a ten-year implementation period have been estimated [44]. These costs amount to a total of $19,825K, with a 1976 present value of $12,949K. This cost data is broken down in detail in Section 4.2.

The ATC benefit cost ratio may be computed from the present value data, as in Table 1.6. These results, a ratio of 9.9, show that RNAV is extremely attractive from the ATC economics point of view.

Table 1.6 ATC Present Value Benefit/Cost Ratio, 1977-2000

Present Value Benefits	\$136.7M
Present Value Costs	13.8M
1976 Benefit/Cost Ratio	9.9

1.3.4 Air Carrier Passenger Benefits

Passenger delay time savings benefits have been computed from the aircraft time savings data discussed earlier, plus average per-flight passenger load data from the CAB report [45]. The resulting savings were costed out at \$12 per passenger-hour, from Reference 51. The total savings, shown in Table 1.7, from 1982-2000 are 588 million passenger-hours (67,000 passenger-years), worth over \$7 billion to the passengers affected.

Table 1.7 Air Carrier Passenger Benefits, 1982-2000

Aircraft Hours Saved	6736K
Average Passenger Load	87.4
Passenger Hours Saved	588.5M
Value @ \$12/hr	\$7062M
1976 Present Value	\$1572M

1.3.5 Overall RNAV Benefit/Cost Assessment

Table 4.29 from Section 4.4 is repeated below, for convenience, as Table 1.8. It includes all of the present value data (abbreviated "PV") presented in this section. Two values of overall RNAV benefit/cost ratio are shown, which differ based on the two airline fuel/time cost assumptions mentioned earlier. These are ratios of 5.5 (low costs) and 7.1 (high costs), either of which illustrate the extreme attractiveness of RNAV from the point of view of economics. As discussed in that section, these become significantly higher if air carrier aircraft equip only with single, rather than dual, RNAV installations.

An additional point of interest due to the fuel crisis, which is also discussed in Section 4.4, is the magnitude of total fuel savings to year 2000. This was found to be (Table 1.3) in excess of 10 billion gallons, which exceeds the 1975 total annual domestic air carrier fuel consumption of 7.3 billion gallons [45].

Table 1.8 Overall RNAV Benefit/Cost Ratios

	Low Cost Assumption	High Cost Assumption
PV Air Carrier Benefits	$1302M	$2193M
PV ATC System Benefits	137M	137M
PV Passenger Benefits	1572M	1572M
TOTAL PV BENEFITS	$3011M	$3902M
PV Air Carrier Costs	$ 442M	$ 442M
PV GA Costs	95M	95M
PV ATC System Costs	14M	14M
TOTAL PV COSTS	$ 551M	$ 551M
BENEFIT/COST RATIOS	5.5	7.1

1.4 UG3RD FEATURE INTERACTIONS

This section discusses relative UG3RD feature priorities and plans, and reviews how the several UG3RD features will interact, given the beneficial influences which RNAV will provide. The results of this study are discussed from the point of view of the effects of RNAV on the ATC limitations which the several UG3RD features are designed to resolve.

1.4.1 UG3RD Implementation Priorities

While all of the UG3RD programs are being pursued on a priority basis, more recently some of these programs have been assigned even higher priority. This was formalized in a list of the ten high priority FAA programs (research and otherwise) published by the Office of the Administrator [41] on October 14, 1975. The resulting high priority programs which are part of the UG3RD set are the following:

- Conflict Alert
- Central Flow Control Automation
- Metering and Spacing
- Minimum Safe Altitude Warning
- Flight Service Station Modernization

This study has determined that there is no reason, from the point of view of RNAV implementation, to disturb the priorities which have been assigned to each UG3RD feature, and has reaffirmed the importance of each UG3RD program area. In the course of this study several areas have been discovered where RNAV and other UG3RD features interact and complement each other to such an extent that certain ATC limitations which have been the motivating force behind development of certain UG3RD features may be relieved, or partially resolved in the short-term environment, through implementation of RNAV techniques. This has no impact on the overall need for any of the UG3RD features, but it does provide the fortuitous benefit of somewhat alleviating certain of the problems associated

with the ATC system until certain longer lead-time programs are implemented. A particularly pertinent example is the Control Message Automation and Data Link combination, which will require a long lead time before providing the controller productivity improvements expected of them. Section 1.4.2, which follows, discusses where this interaction was, and was not, found to exist. The results presented are described in more detail in Section 3.4.

Besides interacting with other UG3RD features, RNAV will interact with the existing VOR route structure. VOR and RNAV high altitude route structures will coexist for a transition time period; low altitude structures may coexist indefinitely. Such situations have existed before, such as when VOR routes were introduced into the LF Range route structure. The resulting dual structure may be more difficult to chart and comprehend, but as shown in Reference 6 it tends to reduce airspace conflict rates, and so doesn't burden the controller. In order to be introduced most efficiently, an RNAV master route structure, designed to be implemented in a phased manner, should be carefully developed in order to realize RNAV benefits while optimizing traffic and route interactions. In Reference 8 the implementation of RNAV is discussed in detail.

1.4.2 UG3RD Feature Interactions with RNAV

The following is a list of the UG3RD features along with a brief discussion of the findings of the study as to the interactions of each feature with RNAV from an implementation viewpoint. In most cases no direct interaction exists. In each case the major motivation behind the development of each UG3RD feature is stated.

NOTE: Explicit definitions of MLS Category I, II and III approach criteria have not yet been specified by ICAO. Usage of the terms "Cat I", etc., are meant to refer to levels of performance equivalent to existing Cat I, etc., ILS capabilities.

- MLS at Dense Terminals -- Wide Beam or (possibly) narrow-beam MLS will be installed at all major terminals so that Category II/III capability may be instituted, allowing improved operational reliability and reductions in weather-induced delays. It is assumed that a narrow-beam Category II/III MLS configuration could be made available, although this is not a currently-planned configuration.

- Wide-Beam MLS -- RNAV provides the area coverage capability in the terminal area to accurately navigate arrival routes and transitions to precision final approach guidance. As demonstrated in Appendix D, the RNAV capability can satisfy the noise abatement procedure requirements at many, but not all, terminals. Therefore, the wide-beam MLS implementation requirement could be eased; this might allow accelerated implementation of the basic and Cat II/III narrow-beam configurations.

- MLS at Small Airports -- Category I, narrow-beam MLS capability is needed at airports where an operational requirement exists. This is particularly true where non-precision approach minimums are high, and where RNAV approach procedures will not adequately meet the operational requirement.

- DABS Surveillance -- The surveillance capability of DABS will be required for certain automation improvements and IPC. It is therefore an important UG3RD feature; however, DABS is not required to support RNAV.

- Intermittent Positive Control -- IPC is primarily intended for the VFR and mixed environments and will provide emergency separation service to non-controlled aircraft.

- Control Message Automation -- Significant reductions in ATC controller workload are expected to result as RNAV is introduced. The basic reasons are the usage of RNAV SID/STAR procedures, of RNAV with M&S, and of an enroute RNAV route structure. CMA (with DABS Data Link) is the major long-term UG3RD program intended for controller workload reduction. The beneficial aspects of RNAV in this area will help ease that problem until CMA is fully implemented.

- Near-Term Automation Enhancements -- Development of these enhancements (Conflict Alert, Conflict Probe, M&S, MSAW, etc.) is well under way. They primarily will improve safety and NAS/ARTS reliability.

- Metering & Spacing -- M&S should significantly improve capacity and reduce delays, and will also function well in an RNAV or mixed RNAV/radar vector environment, as demonstrated in detail in Appendix C.

- Enroute Metering -- This program should result in significant fuel savings.

- Central Flow Control -- Several UG3RD programs, such as M&S, WVAS, ASTC and RNAV, should produce significant airport and airspace capacity improvements, which should result in reductions to delay over the long term. RNAV terminal capacity improvements were demonstrated by real-time simulation [37]. These capacity improvements should help to ease the flow control problem.

- Airport Surface Traffic Control -- Since ground operations must continue during Category II/III conditions at airports where Cat II/III landings are being conducted, ASTC improvements are needed, particularly as Cat II/III capability becomes more widely implemented.

- Wake Vortex Avoidance -- WVAS is critical to improve terminal capacity and reduce delays. WVAS, RNAV, M&S and MLS Cat. II/III will work together to result in a very significant overall improvement to terminal capacity. RNAV capacity impacts are addressed in Section 2.3.1.

- Flight Service Station Modernization -- This program promises that a large potential cost savings will be available upon its successful completion.

It should be emphasized that none of these UG3RD programs are in any way necessary for the successful and beneficial implemenation of RNAV as the primary navigation system.

1.4.3 Extended Capability RNAV Concept Recommendation

A rationale for implementing an Extended Capability RNAV concept (ECR) is presented in Section 3.3.3. The ECR equipment would be required to meet certain performance standards for approval which are considerably higher than present standards [10]. Expended Capability and standard RNAV-equipped aircraft would be fully compatible and coexist in all phases of the NAS environment, with the following exceptions:

- Extended Capability would be required for the conduct of 4D M&S procedures (Standard RNAV aircraft would be integrated with 4D aircraft and conventional radar vector aircraft by the M&S logic).

- A new category of ECR Instrument Approach Procedures would be created.

- ECR capability would be required in order to use the 4D function to achieve reduced in-trail separations under an enroute metering concept discussed in Section 3.3.1.

It should be emphasized at this point that the Extended Capability RNAV concept requires no new or improved navigation aids (DVOR, PVOR or PDME not required). It simply would be an official recognition of the capabilities presently being demonstrated in high quality Area Navigation Systems.

A principal advantage of the ECR Concept is that instrument approach capabilities would be significantly improved, allowing lower decision heights and reduced visibility minima in comparison to standard RNAV procedures. Such a capability would allow operation to minimums which would be, in many cases, significantly lower than existing non-precision approach minimums; this could provide enhanced operational capability at airports prior to deployment of small community MLS systems, and for remaining non-instrumented runways after MLS is installed at primary runways.

1.5 SUMMARY OF CONCLUSIONS

The conclusions of this study are presented in detail in Section 5. The principal findings of this study are presented below.

- The trend to RNAV route structures and the usage of pre-planned direct flight plans will not detrimentally affect DABS site coverage requirements, DABS data link channel usage, or IPC requirements (Section 2.1; Appendix A).

- DABS/IPC could easily transmit control instructions in RNAV terms to equipped aircraft. This could be extended to the point of providing route definition data (Route Data Delivery concept) to aircraft desiring such service (Sections 2.1.2, 2.1.3; Appendix A).

- The only facet of Flight Service Station Modernization plans that would be affected would be that, during the transition to an RNAV environment, a greater number of routes would be stored in the route data base (Section 2.2; Appendix B).

- RNAV procedures may be integrated with metering and spacing techniques without causing any significant procedural or software problems and without affecting arrival time control capability (Section 2.3.1; Appendix C.1).

- The integration of RNAV with M&S improves time controllability (range of delay available) and reduces controller workload. The integration of 4D RNAV procedures will improve arrival time control, time controllability and controller workload (Section 2.3.1; Appendix C.1).

- The logical design of control message automation software will be affected somewhat by the need to service RNAV aircraft, but there will be no significant impact to computer storage or utilization requirements (Section 2.3.2; Appendix C.2).

- Central Flow Control system plans should not be significantly affected by RNAV. Also, RNAV may provide increased holding airspace, which may reduce the dimension of the flow control problem (section 2.3.3; Appendix C.3).

- RNAV provides sufficient accuracy to interface with MLS approach guidance. It may serve as a substitute noise-abatement approach navigation reference in many cases, which may reduce wide-beam MLS implementation requirements. Some noise-abatement benefits may be realized immediately through provision of RNAV routes to intercept ILS approaches (Section 2.4; Appendix D).

- Considerable MLS airborne equipment cost savings would result given that combined RNAV/MLS avionics are developed (Section 2.4.4; Appendix D.4)

- The Airport Surface Traffic Control program will not be affected by RNAV in any way (Section 2.5).

- The Wake Vortex Avoidance Program should not be affected by RNAV except that RNAV control procedures can be beneficially used when changing vortex conditions are detected (Section 2.6; Appendix E).

- No UG3RD program elements were found to either be required for, or to significantly interfere with, the successful and beneficial implementation of RNAV (Section 3.3).

- An Extended Capability RNAV concept was developed in this study which requires no new or improved navaids, but which could significantly reduce MDA's on RNAV approach procedures for appropriately-equipped aircraft (Section 3.3.3).

- An extensive RNAV benefit and cost projection through the year 2000 has shown that the 1976 present value RNAV benefit to aircraft operators, passengers and the ATC system will be more than 5.5 times greater than the costs to those parties (Section 4; Appendix F).

2.0 RNAV IMPACT ON THE UPGRADED THIRD GENERATION SYSTEM

2.1 DISCRETE ADDRESS BEACON SYSTEM/INTERMITTENT POSITIVE CONTROL

2.1.1 DABS Site Coverage, Accuracy and Reliability Requirements

In this section the effects which RNAV implementation would have on DABS surveillance system performance requirements are addressed. Specifically, the following list of DABS performance measures and implementation plans could potentially be affected due to some RNAV system characteristic:

- Tracking Accuracy (range and bearing)
- Track Update Rate (scan period)
- Tracking Reliability (dropouts, garbled responses)
- DABS Coverage Area (at specified minimum altitude)
- Redundant DABS Coverage Area (trackable by more than one site)
- Antenna Site Locations
- Antenna Site Implementation Schedule

Factors bearing on these requirements are heavily influenced by the particular operational environment of interest; and for each such operational environment, only a few in the above list might be candidate potential RNAV impact areas. The situations which were considered as being appropriate for study include the following:

- Enroute IFR Environment (low and high altitude)
- Terminal IFR Environment
- Mixed IFR/VFR (low altitude and terminal)
- Special RNAV Procedures (VNAV, 4D RNAV, approaches)

The results of these studies are treated in detail in Appendix A; the major points are discussed below.

Enroute IFR -- The factors which are candidates for impact include tracking accuracy, site locations and implementation schedules. The tracking accuracy question arises due to the fact that route widths will be reduced in some situations upon implementation of RNAV. However, the accuracy of DABS is so much finer than the route widths (±4.0 nm planned, ±2.5 nm has been suggested) that no changes need be made. The DABS accuracy specification is 0.1° in azimuth (0.17 nm at 100 nm) and 100 ft in range (1σ values).

The antenna site location and implementation schedule effects would stem from the fact that the new RNAV routes would not overlie existing VOR routes, and could deviate from them significantly. In the high altitude enroute environment these deviations could be quite large, since nearly all high altitude airspace has VORTAC coverage, and thus could support RNAV routes. However, it is this high altitude region which is by far the easiest to cover, since terrain and horizon problems have little effect on coverage range of an antenna in most such situations. Long range plans [5] specify that redundant coverage over nearly all CONUS down to 6000 ft AGL is to be provided by the mid-to late- 1980's. Therefore, coverage above FL 180 over most well traveled regions should be available well in advance of that time. The low altitude case is, however, quite different in that 6000 ft AGL will in many areas include IFR traffic (this same coverage plan would provide single coverage to 2000-3000 ft AGL for the most part). However, DABS site implementation plans should not be affected for

two reasons: First, many VOR routes will be retained, which require coverage regardless; second, low altitude route displacements will be small since ordinarily the routes are short so that large deviations are inappropriate, and since even RNAV routes cannot deviate far from the VORTAC presently used to define the corresponding conventional route, due to the limited coverage radius in the low altitude environment.

Terminal IFR -- The DABS performance factors which are candidates for impact due to RNAV in terminal IFR operations are tracking accuracy, update rate and tracking reliability. For terminal route navigation, the tracking accuracy question again arises due to reduced route widths. As before, however, the route widths involved (±2 nm planned; ±1.5 nm has been suggested) are very large in comparison to the tracking accuracy, particularly near the DABS antenna, as these will be. The other tracking accuracy issue concerns the monitoring of RNAV approach procedures. First of all it should be noted that such procedures will be unusual at hub airports since ILS and MLS will be available for the primary runways; RNAV would be used for those non-ILS runways where its characteristics could allow lower minimums. In that event, the terminal-located DABS sites would provide more than adequate surveillance accuracy. The issue of approaches to airports with no resident DABS facility is treated later.

The remaining terminal area problems are update rate and track reliability for self-navigated SID/STAR procedures. The four-second scan rate in present terminal area use is expected to be continued. In comparison to radar vector procedures, the fact that the RNAV SID/STAR routes are self navigated rather than being controlled through ground surveillance could cause the requirement for timely surveillance information to be reduced rather than increased. As a result, neither update rate nor tracking reliability requirements need be more stringent for serving an RNAV environment.

Mixed IFR/VFR -- The major items of potential concern here are tracking accuracy, update rate and reliability, and coverage area. The operational factor of significance is that Intermittent Positive Control service is to be provided for separating VFR/IFR aircraft. However, it makes no difference to the IPC system how an aircraft is navigating; whether VOR or RNAV, the situation to be sensed and service to be provided is the same. Therefore, there would be no accuracy, update rate or reliability impact. Since we are concerned here only with IFR aircraft from an RNAV point of view, the coverage issue is as discussed earlier.

VNAV Arrival/Departure Procedures -- At present all altitude surveillance is accomplished via voice communications and mode C transponder replies. Since VNAV will probably not be used as the primary means for providing altitude separation [8], no changes to these procedures are required. If VNAV were to be used as the primary vertical guidance system, and airspace boundaries were assigned according to the procedures set out in Reference 8 , no improved monitoring would be required. The only situation where surveillance improvements would be needed is that where a highly accurate VNAV system, and correspondingly tight protected airspace boundaries, would be implemented. Such a high performance VNAV capability is not necessary to achieve the fuel conservation benefits discussed in that reference.

4D RNAV Procedures -- An arrival time control accuracy of 5 sec (1σ) has been recommended as a valid target for 4D time control performance, and has been shown to be possible in Appendix C. Such time control procedures, therefore, require a high degree of surveillance accuracy. Since time control procedures would be used only at large hub airports, each of which having a local DABS site, the needed surveillance would occur within ten miles of the antenna. Based upon the DABS specifications stated earlier, at ten miles the azimuth error would amount to 106 feet, and range error 100 feet (1σ). A 100 foot error corresponds to 0.37 seconds at 160 kt, more than an order of magnitude better than the system being tracked, and therefore sufficiently accurate for supporting 4D RNAV Metering and Spacing procedures.

Off-Site RNAV Approach Procedures -- Consideration has been given to a possible requirement that DABS monitoring capability exist in order that an RNAV approach procedure may be defined. This stems exclusively from the fact that more opportunities for data input blunder error exists with RNAV approaches than with some other approach procedures. Ordinarily, it is not expected of the ATC system to be responsible for the execution of an otherwise safe approach procedure. Requiring DABS coverage down to approach minimums would considerably raise decision altitudes for RNAV procedures at airports where no DABS site exists locally, and in many cases would prevent implementation of RNAV procedures completely. Should surveillance be deemed a requirement, however, it is not necessary to monitor the approach down to minimums, but only to the initial segment of the final approach course, some 2,500 feet higher. This would assure that the aircraft is stabilized on the proper course, indicating that RNAV data entry was not erroneous.

2.1.2 DABS Data Link Format and Capacity Requirements

The intent of this study was to determine whether the usage of RNAV as the means of navigation will impose an added burden upon the data link channel of DABS. The context of the study presumed that all planned DABS data link features are in full use, including Intermittent Positive Control (IPC), Control Message Automation (CMA), and Extended Length Messages (ELM). The CMA function is most significantly affected, since clearances would be in RNAV terms rather than conventional navigation terms. The IPC function would not be affected if RNAV clearances are not used. If they were, only the format, not the message count, would change. Usage of RNAV for IPC functions is discussed in the next section. The ELM function was assumed to be not at all affected, since it will be used for weather and other general information, and company communications.

In order to complete the study, an optional RNAV service function was examined. Called Route Data Delivery (RDD), this function would automatically transmit, to inquiring aircraft, waypoint coordinates according to their prefiled flight plan. This would replace multiple waypoint storage and manual data insertion for lower cost systems. It is similar to Digital Data Broadcast [40] except that the data is tailored to the individual aircraft flight plan, and is only transmitted upon demand.

The study is based upon an earlier study, Reference 7, of DABS data link capacity requirements. That study used the projected 1995 Los Angeles Basin Peak Traffic Environment. The present analysis updated that study based on more recent developments in DABS/IPC plans, and then conducted an

equivalent analysis considering a total RNAV environment. In these studies, uplink message rates were determined for the following traffic segments individually:

- LAX Airport Arrivals and Departures
- Enroute IFR Operations at 10,000 Feet and Above (arrivals, departures, overs, withins)
- VFR Aircraft in or Affecting TCA Boundaries
- Extended Length Message-Equipped Users

Downlink message rates were determined individually in the following categories:

- Technical Acknowledgements to Uplink Messages
- MLS Position Monitor Reports
- Pilot Requests

In order to perform an RNAV analysis, the number of DABS message frames (56 bits are available for data per frame) needed for each message type must be known, since total channel usage depends not only on message count, but also on frames per message. To obtain this data, detailed message formats were developed for each message type, RNAV and conventional. The details of this study are reported in Section 2 of Appendix A. A summary of the results, message types and frames required,is presented in Table 2.1. The numbers of frames required are fixed for most messages except for two, for which an additional frame may be tagged on to provide more detailed data. Section 2 of Appendix A presents the detailed study of message rates, starting with a review of the earlier study [7]. The overall findings are presented below.

Uplink Message Rates -- The overall uplink message rates for the entire LAX Basin are presented in Table 2.2. Note that these messages would be divided among (approximately) four individual DABS sites, so that the overall message rates are quite low per site. Note that the IPC messages dominate the rest. This results since they occur in proportion to the square of traffic density, while the remaining messages are in linear proportion to traffic density.

Table 2.1 DABS Frame Requirements for Data Link Messages

MESSAGE TYPE	MESSAGE	Frames	COMMENTS
Vector/Clearance	Radar Vector	1	Basic Heading/Speed/Altitude(uplink)
	Tag Frame	1	Optional Freq/Baro Setting (uplink)
	Proximity Warning	1	For IPC Use (uplink)
	Coded Clearances	1	(uplink)
	Alpha Clearances	4	Eight Characters per Frame (uplink)
RNAV/Clearance	RNAV Control Amendment	1	Offset, Fans, Etc. (uplink)
	Tag Frame	1	Optional Waypoint Data (uplink)
	Route Data Request	1	Request RDD Data (downlink)
	Route Data Delivery	2	Two Frames per Waypoint (uplink)
	Direct Route Clearance	2	Request Direct Routing (downlink)
	Direct Data Request	1	Request Direct Route Data (downlink)
Other Functions	MLS Approach Mon.	1	(downlink)
	Capability Report	1	Aircraft Status (downlink)

Table 2.2 DABS Uplink Message Rates (Messages/Second)

Message Type	No RNAV	100% RNAV
Total ATC Messages/Sec.	4.0	3.5
Total IPC Messages/Sec.	9.0	9.0
Total	13.0	12.5
ELM Uplinks/Sec.	2.0	2.0

It should be mentioned that the extensive usage of RNAV routes may actually reduce overall uplink message rate, since the traffic dispersal effect of RNAV tends to reduce conflict count. No such effect was quantified or included in Table 2.2.

Downlink Message Rates -- The downlink rates, shown in Table 2.3, consist of three components. The first are the technical acknowledgements of the uplinked messages. A technical acknowledgement consists of verbatim retransmittal of the uplink message on the downlink reply. ELM messages are not technically acknowledged. The second category is pilot requests; the rate for them is taken from the earlier study. The third category, MLS position reports, is based on the assumption that four active arrival runways will be in use, and that reports will be issued every second. Note that this is a special case; only one DABS site would be receiving these reports, and so probably represents a site specially configured for MLS report processing.

Table 2.3 DABS Downlink Message Rates (Messages/Second)

Message Type	No RNAV	100% RNAV
Uplink Technical Acknowledge	13.0	12.5
Pilot Requests	0.4	0.4
MLS Position Report	12.0	12.0
Total Downlinks/Sec.	25.4	24.9

RDD Message Rates -- The overall message rate due to the Route Data Delivery optional feature would obviously depend upon the proportion of aircraft which avail themselves of the service. The assumption used here was that 50% of all IFR aircraft would use RDD. The results are expressed in Table 2.4, which shows that uplinks would increase 0.9 messages/second (6%) and downlinks would increase 1.0 messages/second (4%) as a result of the RDD function. Therefore, the use of RDD barely even affects message rates, and so could be handled quite easily by the DABS system.

Table 2.4 Route Data Delivery Option Message Rates (Messages/Second)

Message Type	Rate
Data Uplinks	0.9
Data Requests	0.1
Technical Acknowledgments	0.9
Total Downlinks	1.0

The operation and capabilities of RDD differ vastly from a Digital Data Broadcast (DDB) system (see Reference 40 for a description of the DDB concept). DDB is designed to relieve workload burden and blunder potential for lower-capability-RNAV-equipped users in terminal area operations at hub airports. It operates by encoding waypoint data for all SID/STAR routes in use in the DME (TACAN) ground responder signal. The airborne unit decodes and filters through the data stream, picking out the needed data and storing it. The ground system is relatively simple, since the same "data tape" is played over and over again until runway orientations change. Airborne access time for a given route is on the order of thirty seconds. In contrast, RDD functions by supplying waypoint data specific to each flight (and already known by the center computer) upon demand through the DABS data link. Multiple waypoint storage need not be required of the airborne system. Also, no separate airborne decoder unit is needed. RDD would provide data throughout the flight, not just at busy terminals, although the busy terminals are where such a feature would be most needed.

2.1.3 RNAV Integration with IPC Usage

Integration of RNAV control commands with the IPC system can have several benefits, and airborne system complexity would increase only slightly in the process of adding RNAV control message display capability. These benefits would apply only to IFR RNAV flights and VFR RNAV flights where a flight plan indicating usage of RNAV is filed. One of the problems of IPC is that, while it acts to prevent a conflict, it does nothing to return a pilot to his original course after the threat has passed. RNAV procedures, however, such as parallel offsets, direct-to-waypoint and cancel offset commands, maintain navigation in the cockpit with the following effects:

- No disruption of navigation function.
- Continuous pilot orientation with respect to intended route
- Automatic course reacquisition after passage of threat

Such a technique would have no impact on DABS message rates, since two messages are required for standard IPC (set IPC indicator and, after threat has passed, blank indicator). However, since RNAV would prevent pilot disorientation, pilot acceptance of the IPC concept could be enhanced considerably if RNAV messages were employed.

2.2 FLIGHT SERVICE STATION AUTOMATION

2.2.1 Introduction to the FSS System

The Flight Service Station system consists of a network of 292 Flight Service Stations and the associated communications facilities required for communicating with the Weather Message Switching Center (WMSC) , ARTC Centers, TRACONS and Towers, and each other. The system provides two major functions: weather data collection, processing and dissemination in the form of pilot briefings, and flight plan processing, mostly for general aviation operators. The FSS Modernization Program, an UG3RD element, is aimed at eliminating the inefficiencies inherently present in the obsolete communications systems presently used, in the manpower-intensive nature of the flight service task, and in the widely decentralized nature of the present Flight Service System. The solutions proposed include participation in the development of a new communications system (INACS-Integrated National Airspace Communications System), development of an automated weather processing and flight plan filing capability, and centralization of FSS facilities into a few hubs. This section shall describe present FSS functions and methods, the planned improvements, the integration of RNAV into FSS procedures, and the impacts of RNAV on FSS capabilities and functions. Finally, a further optional function of FSS to aid RNAV users, by providing flight planning assistance, is briefly discussed.

FSS Functions -- The Flight Service Station currently provides the following thirteen functions:

- Pilot Weather Briefings
- Emergency Flight Assistance
- IFR Flight Plan Filing
- NOTAM Processing
- ATC Communications Relay
- Processing of PIREPS
- NAVAID Monitoring
- Enroute VFR Communications
- VFR Flight Plan Filing
- Airport Advisory Service
- Administration of Airman Exams
- Surface Weather Observations
- Military Flight Services

In one of the original studies aimed at modernizing the FSS system [16], it was recommended that the last five items on the list be eliminated or transferred from the purview of the Flight Service Stations. Since that time, however, it has been decided to retain VFR flight plans, and no decision has been made on airport advisory service. Administration of airman exams will definitely be transferred, and weather observations will be transferred, automated or contracted out. Military usage of remote terminals accessing the nearest FSS hub will eliminate direct contact with FSS personnel for the most part.

FSS Facilities -- Current facilities include teletype communication nets (separate for weather data and for ATC facilities flight plan data interchange), and certain voice links. The system is comprised of 292 individual flight service stations. Weather briefing procedures consist of manual compilation and filtering of tabluated and graphic material to obtain data oriented towards a given intended route of flight. Flight plans are recorded manually and communicated by teletype to the affected center, TRACON or FSS. Weather data is observed and recorded manually and communicated by teletype.

2.2.2 Modernized Flight Service Station System

As currently planned, the Flight Service Station Modernization Program [24] will consist of three distinct phases. The automated system will be completed in the second phase (Baseline system), whereas the improvements scheduled for the third phase will be required before the total desired improvement in efficiency is fully achieved.

Near Term Improvements -- These improvements are to be initiated immediately and will serve to improve both level of service and efficiency. Improvement areas include (where needed) physical plant improvements, more modern display equipment, increased Pilot Automatic Telephone Weather Answering Service (PATWAS) and Transcribed Weather Broadcast (TWEB) availability and coverage, Enroute Flight Advisory Service (EFAS) implementation, and certain staff relocations.

Baseline System -- This intermediate term (1980-85) phase will include development and implementation of the automated capability for aiding the Flight Service Specialist, and preparations in anticipation of consolidation. Certain Flight Service Stations will be consolidated into the FSS hubs as the hubs reduce demand on those stations.

Enhanced System -- This long term enhancement, to be initiated in 1983, will result in the complete consolidation of FSS activity into the twenty hub stations. Expanded automated capabilities, including automated user initiated weather briefings and flight plan entry, will be implemented.

2.2.3 Impact of RNAV on FSS Modernization Plans

Nine basic functional areas of the FSS were organized from the thirteen areas listed above in a manner such as to improve the visibility of RNAV impact. Primarily, the usage of charted RNAV routes was presumed and served as the focus of the analyses. However, the preplanned direct concept was also considered. Any areas where preplanned direct could have a significant impact were so identified and analyzed. The results summarized here are discussed in detail in Appendix B.

Surface Weather Observations and Airport Advisory Service -- No impact, in that observations are not conducted on a route-specific basis, and that airport advisories concern only airport-oriented weather and operations data.

NAVAID Monitoring and PIREP Processing -- The only impact would be that there will be more routes for which flight check and PIREP data must be correlated and distributed. With regard to preplanned direct RNAV, PIREPs will no longer be charted-route-oriented, but will be geographic-area-oriented, requiring a slightly different approach to PIREP processing.

Mass Pre-and In-Flight Weather/NOTAM Briefings -- No impact, in that the material is oriented to general areas (NOTAMs may apply to specific routes, which could be either RNAV or conventional; but in terms of impact on FSS plans, this is insignificant).

Individual Pre- and In-Flight Briefings -- If current automated (AWANS system) procedures are continued, no impact exists since weather data organization is accomplished with respect to the origin-destination great circle path, not a specific route. Should route-specific data organization become implemented, RNAV does increase the number of potential routes.

IFR/DVFR Flight Plan Processing -- RNAV and conventional route filing formats are sufficiently similar such that no significant impact on flight plan processors would occur, except that the increased number of routes available, which must be stored to accomplish data validity checking, could have an impact on system complexity. For preplanned direct RNAV using published waypoints, no further impact occurs. If arbitrary waypoints were to be used, only gross error checking would be required.

VFR Flight Plan Processing -- Since VFR flight plan routes need not be validity-checked, no RNAV impact is foreseen.

Emergency Flight Assistance -- Other than that FSS personnel should be familiar with RNAV procedures, there is no significant impact.

ATC Communications Relay -- Other than, again, requiring RNAV familiarity, no RNAV effect is foreseen.

Airman Examinations -- FSS will discontinue administration of airman examinations.

2.2.4 Optional Provision of Flight Planning Assistance

While flight planning assistance could be provided to all categories of users, this discussion is limited to the RNAV preplanned direct case, since flight planning assistance needs are considerably larger in that case. As discussed in detail in Appendix B, many items of information are needed in order to file a flight plan:

- Minimum Altitudes (MOCA, MRA)
- Waypoint Locations
- VORTAC Assignments and Changeover Points
- Determination of Signal Coverage Adequacy (strength, accuracy)
- Restricted Area Avoidance

When planning an arbitrary route, a pilot presently has no suitable guides as to guaranteeing adequacy of signal coverage and minimum reception altitudes, although, presumably, a special series of signal coverage charts could be produced. The other items of information are obtainable from existing charts and through standard graphic or computational procedures, although the entire process is quite complex and time consuming. While automation of these procedures by the FSS would not be a straightforward or easy task (particularly the signal coverage problem), such a capability could be a significant service to GA operators, and may open the way to significant improvements in flight efficiency and fuel savings. Therefore, it was considered desirable to mention this subject even though it is not presently a planned FSS improvement.

2.3 UPGRADED ATC AUTOMATION

2.3.1 Impact of RNAV on Metering and Spacing

The intent of this analysis is to evaluate present plans for developing and implementing Metering and Spacing (M&S) capability in the context of an RNAV, or RNAV-transition, environment. In addition, the specific impact of 4D RNAV procedures in excess of that of basic RNAV is to be determined. The impact areas to be addressed include effects on procedures (airspace and general route layouts), performance (degree of time control afforded, arrival gate delivery accuracy), controller workload, and ARTS computer requirements. This study utilizes as its basis a recent report which defines in detail an M&S system implementation for the Denver terminal area (Reference 30).

The primary motivation behind the implementation of M&S systems is to increase airport capacity without requiring new runway construction, and without requiring new aircraft landing systems, guidance techniques, surveillance systems or wake vortex avoidance systems. Even as other systems are developed which improve airport capacity, M&S capabilities will still be required to take full advantage of the available runway capacity potential of these other systems. The effects which RNAV and 4D procedures will have on M&S performance is therefore the most important subject to be addressed. This section summarizes the methodology and results presented in the detailed analysis contained in Appendix C.

Present M&S Plan -- Metering and Spacing techniques have been under development by the FAA since the late 1960's. Metering and Spacing schemes operate by first metering traffic into the terminal area such that the arrival rate equals runway capacity, considering that departures must be accommodated. Metering is accomplished through scheduling of holding pattern departures. Once the arrival aircraft depart the arrival fix, a landing/departure schedule is established which considers the arrivals and requested departures. From that point the spacing function takes over, unless some event occurs to cause the schedule to be adjusted. The spacing function is accomplished through path length and speed control. The basic time control technique is to provide airspace and route flexibility for two time control areas. The first area offers a large degree of control ($\sim$300 seconds) which is used for correcting the projected final approach gate arrival time to meet the scheduled arrival time. The second time control area provides a limited degree of control, and is used for correcting time delivery errors which build up while traversing the first control area, and for accommodating any minor last minute changes to the scheduled gate arrival time. The most recent plans [30] utilize such a scheme. It is designed in a manner such that a minimal amount of airspace is required (see Figure C.1) for the path stretching function.

RNAV Integration Considerations -- The concept of a common M&S system where both RNAV and conventional aircraft would be accommodated has been studied in the past (References 35,36). The latest plan [30], for the Denver area, does not explicitly consider RNAV traffic. The techniques of References 35 and 36 have been reviewed and modified to produce a technique which is directly applicable to the Denver M&S plan. A set of ground rules for developing RNAV procedures has been established which recognizes the airspace design, ATC control, and RNAV procedural problems which bear on this issue:

- The basic M&S routes and geometry used with RNAV should be in common with standard M&S routes, such that airspace is conserved and video map clutter is reduced.

- The control capability (time controllability and gate delivery accuracy) of RNAV aircraft should be equivalent to or better than the standard capability.

- RNAV procedures used should be convenient to both the flight crew and controller.

- It should not be routinely required for the controller to communicate extensive data, such as waypoint coordinates.

These ground rules impose constraints on the resulting RNAV procedure design. This raises the question of whether it is worth while to integrate RNAV operations within the M&S technique. The answer is that there are several advantages to be realized for both the flight crew and the ATC system. First of all, RNAV terminal procedures have been shown to be both efficient and convenient, in comparison to standard procedures, in analytical studies [8] and in a recent real-time simulation study [37] (see discussion of RNAV benefits in Section 1.3). Secondly, RNAV M&S would be accomplished through the use of published RNAV M&S STAR procedures (see example, Figure C.3). This provides the distinct advantage of maintaining flight crew orientation and self navigation capability throughout the procedure. Third, reductions in controller workload would be expected to result, as is discussed later. Fourth, and perhaps most important, RNAV routes and procedures must be established before the 4D RNAV time control capability may be implemented. 4D RNAV is expected to further increase runway capacity (and reduce delays) through accurate control of arrival timing.

Each of the above RNAV design ground rules, and the resulting RNAV M&S plan, are discussed in detail in Appendix C. The plan which resulted is shown in Figure C.2. It is based on usage of a published M&S STAR procedure (Figure C.3) as the source of navigation information and waypoint coordinates data. All route legs are flown in the "TO Waypoint" mode; no "FROM" operations are allowed, in order to be compatible with airline-type RNAV systems. No impromptu (not shown on chart) waypoints are used. While the RNAV procedure could be based on the "Direct-To-Waypoint" RNAV procedure, a modification of that procedure, whereby the inbound track bearing is specified by the controller, was selected in order to reduce controller workload (discussed later). The resulting routings duplicate virtually exactly the paths which radar vectored aircraft would follow.

Comparative Performance Analysis -- A comparison of the performance, meaning overall time controllability and gate delivery accuracy, of the basic radar vector technique with both the standard RNAV technique and the 4D RNAV technique has been performed, and is documented in detail in Appendix C. In each case, gate delivery error has been determined to the 2σ probability level (95.44% confidence). Also, time controllability, the difference between the maximum and minimum time paths, has been established as that amount of controllability which would be available at least 95.44% of the time, resulting in an equivalent confidence level.

The values for system errors for the case of radar vector control (wind forecast error, heading and speed control errors, surveillance system error, etc.) are taken from the recent Denver M&S analysis, Reference 30. The values selected are, of course, very important since they affect both 2σ gate delivery accuracy and 95.44% confidence time controllability. The values for RNAV system errors were taken from the results of a recent comprehensive RNAV flight test program [31]. All of the error component values are listed in Appendix C. In that flight test program a station-referenced general aviation RNAV system and an air carrier system were tested. The air carrier system was tested in two modes: VOR/DME/Air Data navigation, which is the method expected to be typical of airline-type systems (meets the ARINC 583 Characteristic specifications) and dual VOR/dual DME/Air Data navigation, which is representative of even more advanced systems. Inertial navigation was not tested. Each of the systems performed significantly better than the minimum requirements for terminal area RNAV performance stated in FAA Advisory Circular 90-45A (Reference 10). As would be expected, air carrier system performance was much better than general aviation system performance, and the multiple-VOR/DME system was best of all. These results are discussed in Appendix C. Since nearly all busy period operations at the critical M&S terminals will be air carrier/corporate type aircraft, the ARINC 583 type system results were used as representative of RNAV performance for M&S purposes. The multisensor (multiple VOR/DME) system was considered to be representative of advanced, 4D RNAV systems. It is important to the purposes of the M&S analysis to make a distinction between typical expected performance and minimum allowable (AC 90-45A) performance. Route widths must be based on minimum system performance. The analysis of typical expected M&S performance can, however, be based upon typical system performance, as established by flight test.

The results of the performance analyses, described in Appendix C in detail, are summarized in Tables 2.5 and 2.6. Table 2.5 shows the 95.44% confidence level results for the three techniques based on the use of identical route geometry. In each case the controllability obtained is significantly greater than that derived in Reference 30. This is simply a result of the fact that the geometry selected here allows longer path lengths than in [30], but could be cut down to match that design. The significant result in Table 2.5 is that RNAV provides a 6% increase, and 4D RNAV a 20% increase, in controllability over the same route geometry. This results since the cross track accuracy of RNAV (and particularly the 4D system) is much better over long legs than radar vector accuracy. Only on the very short legs is the radar vector technique more accurate. Furthermore, the along track control accuracy of the 4D RNAV system is much greater than the open-loop case, further enhancing controllability.

Table 2.5 M&S Controllability (95.44% confidence)

Region	Radar Vector M&S	M&S + RNAV	M&S + 4D RNAV
Downwind/Base Leg Final Approach Intercept	270.7 sec 27.7 sec	293.5 sec 23.7 sec	312.2 sec 47.6 sec
Overall	298.4 sec (5.0 min)	317.2 sec (5.3 min)	359.8 sec (6.0 min)

The other performance measure, gate delivery accuracy, is posted in Table 2.6. For each of the three systems, the gate delivery analysis was performed over the longest and shortest leg lengths, resulting in the two numbers listed in each column in the row labeled "Gate Delivery Error". In the standard M&S case they are equal. In the RNAV M&S case, the long leg value is virtually the same, while the short leg value is 1.4 sec longer. It should be emphasized that this larger value occurs only at the extreme, the very shortest leg. On all legs in between, the delivery error is similar to that of the longest leg. The delivery error of the shortest leg can be reduced by substituting one radar vector for one RNAV command, but in operational usage this occasional minor perturbation would probably be ignored. Thus, RNAV M&S gate delivery performance is equivalent to radar vector performance. The 4D system shows a distinct improvement, however, of 33%. The reduction to 7.2/7.4 sec from 10.8 sec results directly from the time control capability, and would be expected over all of the various intermediate length legs. This improved performance with 4D does not depend upon the usage of the highly accurate DABS surveillance system. ATCRBS is sufficiently accurate (at short ranges) so as to allow desired 4D M&S system performance.

Table 2.6 M&S Gate Delivery Accuracy

	Radar Vector M&S		M&S + RNAV		M&S + 4D RNAV	
Control Extreme:	Long	Short	Long	Short	Long	Short
Gate Delivery Error (2σ)	10.8 sec	10.8 sec	10.9 sec	12.2 or 10.8* sec	7.2 sec	7.4 sec
Interarrival Spacing (1σ)	7.6 sec	7.6 sec	7.7 sec	8.6 or 7.6* sec	5.1 sec	5.2 sec
Earlier Analysis (1σ)	11 or 8 sec		11 or 8 sec		5 sec	

*Smaller value presumes use of one radar vector command for final approach intercept.

In order to compare these results with earlier M&S performance analyses, values for 1σ interarrival spacing are derived from the delivery error data, and listed in Table 2.6. Reference 32, an analytical study, derives interarrival error values of 11 sec for M&S and 5 sec for 4D M&S. Reference 30, the Denver design study, lists 8 sec as the M&S target. Reference 33, a cockpit simulation study, obtained a 4D RNAV performance of 5.4 seconds. As is shown in Table 2.6, the 8 and 5 second values, respectively, are substantiated by the present analysis.

Controller Workload Implications -- Analysis of the M&S procedure in Appendix C shows that a total of five ATC control instructions are required to perform the M&S procedure. This is true also with the RNAV version of the procedure. The difference is that each command in the radar vector case is time-critical, in that it must be delivered to the aircraft at exactly the right time so that the maneuver is performed at the proper time. In the RNAV case, if the technique of specifying the inbound track bearing to the objective waypoint (rather than simply the "direct-to" instruction) is used, all but one of the five control commands is no longer time-critical. It may be issued several seconds ahead of the intended turn time at the controller's convenience. This relieves a considerable burden from the controller by simplifying his task of organizing himself and his communications. The one remaining time-critical message is the speed reduction as the aircraft approaches the gate.

In the 4D RNAV case, workload is diminished further in that not only are the original four messages not time-critical, but the fifth, the speed reduction, is eliminated with 4D. Tending to work against these workloading reductions is the fact that more information (waypoint name with RNAV; arrival time -- but not speed -- with 4D) is transmitted in each message. However, these factors are expected to be outweighed by the basic improvement resulting from RNAV. The use of 4D also implies air-ground time synchronization which could be performed automatically with DABS. Even without DABS, this does not increase workload at critical times, since the synchronization may be accomplished at any point during, or before, the flight.

Computer Requirements Effects -- The RNAV procedures described here are similar enough to those used in Reference 34 to consider the findings of that study to remain valid. It was found in that study that a very nominal increase of 450 words (in addition to the 16,000 required for basic M&S) is needed to accommodate RNAV. There was found to be no execution time impact. No similar analysis exists concerning 4D RNAV usage. Since the 4D concept is just a simple extension of the basic RNAV concept (waypoint arrival times would be assigned internal to the basic RNAV system anyway), the resulting impact would be very small.

2.3.2 Impact of RNAV on Control Message Automation

The objective of this analysis is to determine what, if any, impact RNAV will cause in terms of Control Message Automation (CMA) system complexity, and resulting computer core requirements, execution time, and DABS data link channel usage. The CMA feature is very important from the point of view of ATC efficiency, since it is expected to significantly enhance controller productivity and, therefore, reduce ATC staffing costs.

CMA system capabilities are planned for several future uses:

- Automatic generation and delivery of Conflict Prediction and Conflict Alert system commands

- Automating the routine control communications required for Metering & Spacing

- Generation and delivery of routine control messages (speed and altitude changes, clearances, etc.)

Eventually, the majority of routine ATC communications are to be automated.

CMA Functional Breakdown -- The Control Message Automation system can be thought of as consisting of six functional elements

- Automated Monitoring -- Aircraft tracking, including, for some functions, association with the intended route or path, such that path deviations and route progress are always known.

- Problem Recognition, or Strategy Development -- This function, for example, would be the conflict detection phase of Conflict Alert, or the arrival time calculation and path assignment portion of M&S.

- Control Action Decision -- The actual decision to effect a specific flight path deviation, or deliver a specific clearance.

- Message Formulation -- Derivation of a specific message (to the controller, or via DABS) appropriate to the situation.

- Transmission and Verification -- The physical act of forwarding a message to a control console or to a DABS site, and communicating the message.

- Compliance Monitoring -- Determination of proper aircraft compliance, and corrective action formulation where necessary.

Of these six elements, two could potentially be affected by RNAV: Control Action Decision and Message Formulation. The first could be affected since the presence of an RNAV flight plan would change somewhat the planning strategy, since it is desirable to keep an RNAV aircraft on an RNAV flight plan, and since under some conditions RNAV can provide more attractive conflict avoidance maneuvers than, for example, the altitude reclearance. The second obviously is affected since now more message types must be handled.

RNAV Impact Assessment -- The impact on the Control Action Decision phase is simply that the logic will have to be modified slightly, which will result in no significant change to core requirement or execution time. Determining impact for the Message Formulation phase is, however, somewhat more complex, as indicated below. These considerations are discussed in more detail in Appendix C.

First of all, to completely handle RNAV, two or three more message types would be required, which would necessitate additional complexity. The actual computations required to generate the RNAV messages would be, however, no more complex than those required for conventional control. Since the parallel offset maneuver would require on the average fewer messages to complete than a similar radar vector procedure, message count would decrease. Therefore, CMA used for conflict resolution activities would require a small increase in core memory, but would result in a slight reduction in execution time requirement. Concerning M&S, as discussed in Section 2.3.1, message frequency would be the same, although only one additional message type is required, rather than two or three. 4D RNAV reduces message rate but adds one more message type. Concerning routine control messages (speed, altitude, barometric setting, clearance, etc.), message rate is reduced slightly, as shown in the DABS channel capacity analysis in Appendix A. Concerning the use of RNAV SID/STAR procedures (where M&S is not in use) instead of radar vectors, message count drops dramatically since the procedure is pre-defined.

It appears that the most significant RNAV impact on CMA will be in development of the computer logic. A small increase in core requirement will result although the execution time requirement is shorter. All of these effects are minor, particularly when viewed in the context that the two CMA functional elements affected constitute only a minor portion of the entire CMA process.

2.3.3 Impact of RNAV on Central Flow Control

The Central Flow Control (CFC) concept is oriented towards minimizing airborne delays and preventing airspace congestion through nationwide data collection, planning and flow control on a day-to-day basis. Two basic functions are performed in a CFC system: collection of demand and capacity data for major high-delay airports and forecasting of high delay situations; and nationwide coordination and control of traffic to minimize the impact on aircraft operators and the ATC system.

Insufficient terminal capacity can stem from chronically excessive peak demands or from temporary situations where weather or other factors reduce capacity. Capacity imbalances not only cause added expense and inconvenience to the airspace users, but the excess arrival traffic can saturate available holding airspace at the ARTC center involved and spill over into adjacent centers, compounding the airspace saturation problem.

Present CFC System and Procedures -- At present the Central Flow Control facility is organized as part of the FAA Systems Command Center. Automated facilities are used to predict excessive demand situations at the major high-delay airports. The primary demand data base is the Official Airline Guide (OAG), as updated by airport reservations requests. The capacity data base is updated by teletype reports from the terminals involved. Three specific flow control procedures are used at present:

- Standard Intercenter Flow Control -- direct negotiation between centers to limit traffic influx bound for a saturated terminal

- Fuel Advisory Departures -- ground delay advisories furnished to scheduled departing operators for fuel conservation purposes

- Quota Flow Control -- formalized procedure where each center adjacent to the saturated center is assigned a specific traffic quota, and must hold all other arrivals.

These procedures are discussed further in Appendix C. Since the effectiveness of these procedures depends upon comprehensive, timely and accurate information, an advanced automation capability is scheduled for development.

Planned Flow Control Improvements -- The automated flow control system which is planned (see Appendix C) will utilize a dedicated computational capability. This system will have direct links with the computers at each of the twenty centers to provide real time updates to the OAG data base. Delay predictions and flow control procedure decisions will be further automated and improved. Dissemination of messages to involved ARTCC's will be automated. Also, the system will be able to provide traffic demand data at predetermined key enroute fixes in addition to the terminal data currently provided. The result will be a system which performs much the same function of the present system, but which will be much more highly automated and accurate due to the real time update capability.

RNAV Impact Assessment -- RNAV can provide two capabilities which can be of benefit to the CFC function. First of all, RNAV may be used in some cases to provide additional holding fixes at arbitrary points, increasing airspace capacity at the affected center, and so reducing the amount of CFC activity required. Secondly, an RNAV route structure would provide added options for congested area avoidance when it is necessary to provide alternate routings for conflicting traffic. The flow control process, as presently planned, is not route-oriented; e.g. the origin/destination pair is of importance but not the exact route of flight. Therefore, the presence of an RNAV route structure does not significantly impact CFC in any other way.

2.3.4 RNAV Impact on Other Automation Features

Conflict Alert and Conflict Prediction Systems -- It has been demonstrated through the use of fast-time simulations in the enroute environment [6] that the addition of an RNAV route structure tends to diminish the number of airspace conflict situations which occur. This is true such that, if all aircraft operated on RNAV flight plans, conflicts are reduced. Also, during the transition to RNAV operations there would be fewer conflict situations due to the larger number of routes in use. In terminal airspace, the usage of RNAV SID/STAR procedures with integral altitude restrictions minimizes conflict potential in that environment also.

Should preplanned direct RNAV operating become commonplace, conflict count still will not increase significantly, although the nature or types of conflicts (crossing, rather than common route) will change.

RNAV provides for the controller added options for dealing with conflict situations. These options, discussed in detail in Reference 15, can be used both to reduce controller workload and save on aircraft operating costs. The primary option, the parallel offset, does both. Since the offset is self-navigated, controller monitoring and communications workload is reduced. Being more attractive to the controller, if they are used rather than altitude re-clearances, fuel savings to the aircraft involved can result.

Flight Plan Conflict Probe -- Once a flight plan has been processed and converted to center coordinates, there is no distinction between an RNAV or conventional flight plan as far as the conflict probe algorithm is involved. Therefore, RNAV routings have no effect on the conflict probe system. This would remain true even if preplanned direct flight plans were to become commonplace.

Minimum Safe Altitude Warning -- No RNAV impact is foreseen in this area.

Control Sector Design -- Improvements are planned to the physical facilities furnished as a part of each control sector console. The major improvement is to provide flight plan display capability such that the manual flight data controller position can be eliminated. While RNAV flight plans will affect the specific information displayed, there will be no effect on the physical characteristics of the improvements themselves.

Enroute Metering -- Enroute Metering is a function which can be provided as a part of the Local Flow Control (LFC) process. Enroute Metering is the process whereby a low-speed enroute transition segment is substituted for unproductive holding pattern time. This could save a significant amount of fuel. RNAV will have no impact on the Enroute Metering function itself. However, 4D RNAV capability could be used in conducting the delay procedure.

2.4 MICROWAVE LANDING SYSTEM

2.4.1 Introduction

The Microwave Landing System (MLS) development program was motivated by several deficiencies in the present ILS system. These deficiencies are both operational and economic in nature, with these two criteria interacting to some extent. The basic deficiency of the ILS system is that it is a continuous wave system operating in the VHF/UHF frequency band, which means that the signal can be seriously disturbed through multipath reflection effects. This problem limits the applicability of ILS for providing Category II approaches, and can prohibit ILS implementation at many airports due to extremely high site preparation costs. In addition, ILS can provide only one approach path, whereas an operational need for variable path and gradient procedures can be demonstrated. The result is a need for the MLS program, whose objectives were established as follows:

- Develop a new precision landing guidance system by 1977 which will have increased performance compared with today's UHF/VHF ILS system and will require less costly and stringent requirements for site preparation and installation.

- Develop a basic system with the capability of increased performance through modular additions so that the capability and cost can be tailored to satisfy differing requirements of various airports and users.

- Provide for curved, multiple approaches so that approach paths can be selected for minimum noise impact on the community consistent with aircraft flight characteristics. This improvement in flexibility of the service relates directly to the overall goal of improving performance.

- Provide a single standard for the signal-in-space which will satisfy the principal needs of the civil, military, and international users. Not only would this eliminate the additional costs of several proliferating systems, but it would add to the safety of emergency operations, permitting, for example, a precision approach of a civil aircraft at a military installation.

- Complete essential development at a sufficiently early date to ensure availability for evaluation by other ICAO members.

The resulting MLS system will allow precise measurements of azimuth, elevation and range from the ground sites. Expanded configurations will include wide-beam proportional coverage (±40°) and Category II and III capabilities, which will include additional signals such as flare guidance and missed approach guidance.

The RNAV and MLS systems were designed for two specific different purposes: RNAV for enroute and terminal navigation, and MLS for precision approach and landing. There is a great deal of potential overlap between the two since the

MLS was designed to provide a degree of area coverage near the runway, which is a function normally ascribed to Area Navigation. Since there is functional as well as operational overlap, and since there necessarily will be an RNAV/MLS transition point somewhere, the following subjects have been selected for study in this RNAV/MLS impact analysis:

- The RNAV/MLS interface problem
  - Lateral
  - Vertical

- Route-following requirements, and usage for the execution of noise-abatement approach procedures.

- Commonality of airborne computational and display requirements, and MLS usage as a 4D guidance sensor.

- Complementary RNAV/MLS functional capabilities.

The results of the analyses of these topics are reviewed in this section, while the detailed analyses are contained in Appendix D.

2.4.2 The RNAV/MLS Transition Problem

The RNAV/MLS transition problem relates to the fact that while the MLS is a highly precise system, the RNAV concept embodies only moderately accurate position-finding techniques as the minimum required capability. Thus, at the interface where MLS data is first received, any RNAV navigation errors will be noted within the MLS system and would then be corrected through the guidance loop. Whether this creates an operational problem or not depends upon the degree of RNAV delivery error to be expected, the geometry of the routes, and the approach taken to the solution of the problem.

An analysis was made of the relative location of the nearest VORTAC station with respect to the 23 major airports in the 20 high density terminal hubs. It was found that for at least 80% of these airports, the VORTAC was within 10 nm of the center of the airport. Referring to AC90-45A [10] (see Table D.2), it may be seen that the maximum 2σ error existing, given a 10 nm range, is a cross-track error of 1.0 nm. Appendix D contains a more detailed analysis of the effects of VORTAC/runway geometry on cross-track accuracy. It should be recognized that this 1.0 nm value is an outer limit; most airline and corporate-type RNAV systems are expected to show far better performance (see Table D.3).

Three possible procedures could be used for correcting the RNAV delivery error and capturing the MLS track:

- Utilize MLS guidance to effect immediate capture of the nominal track.

- Utilize MLS guidance to intercept the nominal track at the next turn point.

- Utilize RNAV guidance to maintain current track to intercept the next segment. Utilize MLS guidance in executing the turn to the following track.

In wide-beam (±40°) MLS environments, Appendix D shows that the first technique is most appropriate. Indeed, the present track at the MLS intercept point may be intercepted using standard control laws under the following minimum final approach leg length conditions: For a course with a 90° turn-to-final (or less), no straight final approach leg segment is required; for a course with a 180° turn-to-final, a 3 nm straight segment would be required (see Figures D.3, D.4, D.5). As beam-width is reduced, these conditions change. In the narrow-beam case (±20° or less), the final approach segment length required is much longer. This is to be expected given use of the first technique shown above since it requires that the present track be acquired, which means that the present track segment within coverage of MLS must be long enough to be acquirable. This problem is eliminated if the third technique above is used. In that case the error on the present leg is considered to be of no consequence, while the next leg is intercepted properly using MLS data. In any case it is not necessary to use severe or otherwise unusual maneuvers to acquire track.

The transition to MLS vertical guidance is somewhat more involved than the lateral case, and is discussed in detail in the appendix. The causes are: (1) limitations on descent rate and the prohibition against an arriving aircraft climbing to zero-out an error; (2) the along-track component of RNAV error at the delivery point; and (3) differences between the geometric altitude measurements of MLS. and the baro-corrected altimetry used for 3D RNAV and standard level segments. Item 1 simply affects system logic. Item 2 presents a situation where the guidance computer, upon receipt of good MLS data, must alter the descent gradient (if gradient descent is in use) in order to compensate for the delivery error. Item 3 is a thorny problem since, although the MLS elevation data is more accurate than barometric data, it is inconsistent with it due to the effects of temperature deviations on the height/pressure profile, even when the local barometric correction is used. This barometric altimetry error (amounting to ∿3%, 3σ) is systematic, such that all baro altitude users are affected equivalently, causing an aircraft operating on MLS data to be apparently in error by comparison. Several solutions to this problem are studied in Appendix D. The recommended solution is based upon the fact that, using the procedures and data from AC90-45A [10] and considering all error sources,during level flight the required vertical separation of aircraft in a mixed (MLS/baro) environment is less than 1000ft. at and below 4000 ft. AGL. Thus,MLS systems would be designed to utilize barometric data (or fly level segments based on altimetry) above 4000 ft., and transition to MLS vertical guidance below.

2.4.3 The Route Following and Noise Abatement Problems

The capability to navigate complex approach paths, including curved as well as straight segments, in order to fly over noise-insensitive areas or to avoid obstacles has long been a recommended feature of the Microwave Landing System. Since this capability implies that a wide-beam MLS feature would be provided, it is of interest to determine under what conditions the highly

precise wide-beam coverage would be actually needed, and under what conditions RNAV guidance could serve the stated purpose. Several examples of existing VFR noise abatement approach procedures which are candidates for conversion to IFR procedures, given the wherewithall to navigate them, are evaluated in the appendix. The first case is the Potomac River Approach to Washington National Runway 18. It was found that such a procedure could be duplicated under IFR conditions using MLS. However, the prohibited areas on either side of the river are so closely located to the approach path that RNAV (using the airspace requirements of AC90-45A [10]) would not be suitable for the purpose. Note that the application of curved segments to the River Approach is not a consideration here; RNAV computers could be programmed to fly curved segments just as easily as an MLS system could.

Another approach procedure examined in Appendix D is typical of the situation at many airports where prohibited areas are not a consideration. This procedure, the Hudson River Visual Approach to La Guardia Runway 13, utilizes the river as a noise abatement corridor to intercept the ILS course to the runway. This is an ideal application of RNAV to provide an IFR noise abatement capability. The RNAV arrival route can be designed with altitude restrictions which ensure obstacle clearance, but which still provide the proper transition to the ILS glideslope (see Figure D.9).

In conclusion, RNAV may be used at a great many airports to define noise abatement transitions to ILS courses for IFR use. The cases where MLS would be required instead are limited to those unusual cases like Washington National, or those cases where the noise advantage can be gained only through the use of an extremely short final approach segment. An outstanding advantage of the RNAV procedures is that they could be implemented in the very near future, without waiting for MLS deployment, since no new ground installations are required.

2.4.4 Functional Compatibility

RNAV and MLS systems share many functions in common. First, and particularly for airline-type systems, route data storage is provided with the RNAV system, and could be applied to the MLS routings. Secondly, each system uses paths defined in terms of waypoints. The fact that MLS may utilize certain paths defined as segments of arcs is not part of the standard RNAV concept, but certainly would not be a significant addition to system complexity. Both types of systems utilize navigation sensor data in some form to derive route progress and track deviation information. Both types of systems would be interfaced to standard flight instruments and autopilots.

The two significant differences between RNAV (as conventionally conceived of) and MLS are (1) that an MLS sensor is employed, and (2) that conventional flight instruments may not be suitable for operations along curved route segments. This display problem is discussed in detail in Appendix D. Basically, the problem is that conventional instruments do not provide the anticipation necessary to correctly follow a curved path. Therefore some new type of instrument, such as an Electronic Horizontal Situation Indicator, may be required.

In order for an RNAV computer to serve as an MLS computer as well, it should be configured to accept MLS sensor inputs and perform the necessary RNAV/MLS interface functions. Additionally, it must of course provide whatever MLS functions are appropriate to the category landings being conducted, such as flare guidance etc. Considerable cost savings can result from taking advantage of RNAV/MLS equipment commonality.

In a 4D Metering and Spacing environment it may be desirable to utilize the MLS data from a time control point of view as well as vertical and lateral control. As a result, even higher time control accuracies, and therefore higher airport capacities, should be achieved.

2.4.5 Complementary Capabilities

In addition to the areas indicated above where RNAV can complement MLS capabilities, two areas remain where RNAV may supplement the capabilities of the less complex MLS installations. First of all, certain community airport applications of MLS will provide only azimuth and elevation coverage, but not range. Where this would be beneficial, RNAV capabilities could be used to provide range-to-touchdown data. The other application concerns Cat I and Cat I/II installations where no back azimuth signal is provided for missed approach guidance. RNAV capabilities could easily fulfill that role, where such guidance is needed.

2.5 AIRPORT SURFACE TRAFFIC CONTROL

No interaction is expected to exist between RNAV and ASTC. At present, no plan exists for development of an autonomous, area-coverage, ground navigation system. The closest projected capability is the usage of MLS roll-out guidance, although this would be specific path guidance and not intended for area coverage purposes.

2.6 WAKE VORTEX AVOIDANCE SYSTEM

The WVAS will consist of various types of sensors which shall either detect conditions which are conducive to development of a vortex threat, or shall detect and track vortices directly. There is no direct interaction between the WVAS and RNAV capabilities. However, RNAV should be very useful as a control tool for providing increased separations required when vortex conditions are detected.

Appendix E evaluates the application of RNAV techniques to vortex avoidance. In summary it was found that the delay fan procedure is appropriate for separating aircraft while the trailing aircraft is not yet on the same path as the vortex-generating aircraft, while the parallel offset maneuver is appropriate when the two aircraft are on a common path. In both cases, the control procedure tends to guide the trailing aircraft away from the threat as well as increasing final approach in-trail separation.

3.0 UG3RD SYSTEM IMPLEMENTATION CONSIDERATIONS

3.1 LIMITATIONS OF THE THIRD GENERATION ATC SYSTEM

The Third Generation ATC System was developed in the 1960's as the beginning of an evolutionary development process by which the level of service provided by the ATC system would be improved, and where the growth in routine manpower costs could eventually be reduced. It should be understood that the 3RD system was intended to be a baseline level of automation which in itself would not dramatically improve service or reduce staffing costs, but which was necessary before those improvements which would do so could be implemented. The automated facilities which were developed are summarized in the following.

3.1.1 Capabilities of the Third Generation ATC System

Enroute Automation (NAS Stage A Model 3d) -- Those features which have been, or which will imminently be, implemented are as follows:

- ATCRBS beacon and primary radar tracking
- Automatic interfacility and intersector handoffs
- Digital display of flight information data
- Automatic flight plan processing, updating and forwarding
- Automatic fix-time updating
- Fail-safe features

Terminal Automation (ARTS III) -- The following features have been, or shall shortly be, implemented:

- ATCRBS beacon and primary radar tracking
- Automated interfacility handoffs
- Semi-automatic position handoffs
- Digital Display of flight information data

In addition, the following enhancements are under development:

- Fail-soft and fail-safe features
- Continuous data recording
- Multi-sensor capability
- Metering and Spacing
- Conflict prediction

Terminal Automation (ARTS II) -- The following features are a part of the ARTS II system (presently under contract):

- ATCRBS beacon decoding, with altitude
- Digital Display of beacon data
- Automated aides for data reception and forwarding

ATC System Command Center -- Several new supervisory functions have been created and integrated in one office. Automated aids have been developed to assist in their operation:

- Central Flow Control Facility (CFCF)
- Central Altitude Reservation Facility (CARF)
- Airport Reservation Office (ARO)

The above Third Generation capabilities are in addition to the continuing improvements being made to the ATCRBS net, the air/ground and inter-facility communications net, the navigation system, the ILS system and the Flight Service system.

3.1.2 Third Generation System Limitations

While the existing system services air traffic to an adequate extent for the most part, increasing traffic (both transport and GA), increasing ATC staffing costs, high delays and continuing accidents prompt the development of enhancements to the 3RD system. These take the form of Upgraded Third Generation System improvements, and will eventually culminate in the Advanced Air Traffic Management System. The major Third Generation System problems are as follows, as described in Reference 52.

Manual Control -- Deliberately, the 3RD system did not provide for automating control decisions and functions. Such automation is considered necessary to achieve significant new staffing cost savings.

ATCRBS Limitations -- Although radar performance has been enhanced by the beacon transponder system, there are certain basic limitations (beam width, synchronous garble, missed and false targets) which would prevent the development of IPC and many automation enhancements, and would render ATCRBS unsuitable for high traffic density situations.

Voice Communications -- Again limiting the extent to which controller productivity may be improved, the absence of a data link capability will also result in continued voice channel saturation problems.

Airborne and Ground Delays -- Due primarily to the inability (cost, location, noise, etc.) to provide additional runway capabilities and effective monitoring and control of ground movements in poor weather, airborne and ground delays continue to mount, particularly as a result of the wake vortex problem.

Oceanic Communications -- Although not of concern to this study, poor communications capabilities continue to hamper oceanic operations and prevent effective control and oceanic airway capacity improvements.

Instrument Landing System -- Due to basic limitations of the VHF ILS system, Cat I ILS cannot be implemented at many airports where it is seriously needed, and Cat II systems become far more costly than would be justified.

Flight Service Stations -- Through wide dispersion of facilities, manual procedures and antiquated communications networks, the Flight Service system operates effectively but in a manpower-intensive manner.

3.2 UG3RD PLANS FOR PERFORMANCE IMPROVEMENTS

The Air Traffic Control Advisory Committee (ATCAC) [13] in 1969 recognized many of the problems stated above, and came forth with the following set of general recommendations for upgrading the capabilities of the Third Generation System:

- Microwave Landing System
- High capacity airport designs
- Wide implementation of RNAV
- A discrete address ATCRBS with data link capability
- Intermittent Positive Control, for ensuring safety in the mixed (IFR/VFR) traffic environment
- Additional automation developments for productivity enhancement

As a result, the nine-point UG3RD program was adopted by the FAA. This section shall review these nine points, detailing the specific problems they are intended to solve.

3.2.1 Discrete Address Beacon System

The DABS system provides vastly improved surveillance performance and a data link capability. The motivations behind the surveillance improvements are:

- To be able to track reliably in a highly dense traffic environment
- To track much more accurately than ATCRBS

These are required to assure high performance of the IPC subsystem, and to allow advanced automated improvements to be implemented. Thus the basic motivations are safety, traffic density, controller productivity and capacity improvements.

3.2.2 Intermittent Positive Control

IPC was discussed above, but it should be mentioned that IPC also tends to relieve controller workload in high density environments.

3.2.3 Flight Service Station Automation

This program will eventually provide equivalent or improved briefing and flight plan filing service to general aviation users. However, the primary, overbearing motivation is Flight Service Specialist productivity. Also, additional automated flight planning services may be provided, serving user convenience.

3.2.4 Upgraded ATC Automation

Metering and Spacing is intended to improve airport capacity and reduce delays. In addition, the automation will tend to reduce controller workload, and so may improve productivity.

Control Message Automation is aimed exclusively at improving controller productivity. It is perhaps the single most effective planned UG3RD improvement for creating productivity increases, and therefore for achieving ATC cost reductions.

Central Flow Control Automation is intended to improve the process by which delays are reduced (or transferred to ground delay), and airspace saturation is prevented. The result will be both lower user operating costs and reduced controller workload. CFC automation improvements will also enhance CFC staff productivity.

Automated Conflict Alert is intended exclusively to enhance the margin of safety in the system.

The Flight Plan Conflict probe is primarily aimed towards reducing controller workload by eliminating potential conflict situations before they occur.

Minimum Safe Altitude Warning is intended exclusively to enhance the margin of safety in the system.

Control Sector Design Improvements are intended solely for staff efficiency improvements.

The enroute metering concept is designed primarily for user fuel savings, although it has ramifications in terms of airspace saturation and, therefore, controller workload.

3.2.5 Microwave Landing System

The MLS is designed primarily to reduce delays and enhance operational reliability. Three primary purposes are to be served by MLS. First, precision landing aids may be installed at many airports where it is now economically infeasible, due to siting problems, to commission an ILS. Second, CAT II and III landing capabilities may be more easily established at large airports. Third, noise abatement approach procedures may be conducted during instrument conditions (these may be presently conducted safely in VFR conditions through radar vectors or visual cues). These all are delay-reducing and reliability-enhancing capabilities; thus they will result in user cost savings and reduced incidence of airspace saturation.

3.2.6 Airport Surface Traffic Control

Surface traffic control is presently a problem at several airports during instrument conditions. Eventual widespread installation of Cat II/III capability will significantly complicate the ASTC problem since aircraft will be operating under even worse conditions. ASTC improvements will reduce delays and also make the ground controller's job much easier, requiring fewer personnel.

3.2.7 Wake Vortex Avoidance System

The wake vortex problem has seriously reduced arrival capacity at virtually all high-delay airports. Significant benefits to aircraft operators will result from reduced delays due to successive improvements to the capability to predict, detect and avoid wake vortex situations. The resulting capacity improvements will make airspace saturation less of a problem, relieving controller workload.

3.2.8 Aerosat

While not of concern to this study, since the objective is the study of domestic RNAV implementation, the Aerosat system will serve both users and controllers through significant communications (and therefore control) improvements.

3.2.9 RNAV

As discussed in detail in Section 1.3, RNAV will provide significant cost savings to aircraft operators and improvements to controller productivity as well. Terminal SID/STAR procedures with altitude separation will considerably improve terminal traffic organization and reduce workload. Enroute structures will reduce travel time and reduce conflict potential.

3.3 RNAV CAPABILITY FOR OVERALL ATC PERFORMANCE IMPROVEMENT

As discussed in the previous section, the UG3RD program is designed to produce specific improvements in terms of several measures of performance, as well as an overall improvement to the margin of safety. The intent of this section is to analyze the effects of RNAV implementation and determine:

- What effect RNAV has on those same performance measures
- How RNAV and the other UG3RD features will interact, and what impact (either compounding or duplication) this has on those performance measures
- How other optional enhancements to the RNAV concept could further improve overall system performance

3.3.1 RNAV Impact on System Performance Measures

Four specific measures of ATC system performance are considered here:

- Controller workload and productivity
- Terminal capacity and delays
- Airspace congestion
- User costs and operational convenience

These are examined both in terms of the basic RNAV impact on the performance measures independent of the UG3RD program, and on the RNAV impact because of interactions with UG3RD program elements.

Controller Workload -- The basic RNAV effects on terminal ATC controller workload stem from two factors: (1) RNAV SID/STAR routes, being self-navigated, reduce communications workload drastically; and (2) established RNAV routings reduce airspace conflict potential since conflict situations are "designed-out". Section 1.3 recites results from a recent RNAV real time simulation. For example, radio contacts per aircraft were decreased by the amount of 20.0% to 39.9% (arrivals) and of 53.8% to 58.6% (departures) by transitioning all traffic to RNAV routes. These effects are not dependent upon UG3RD implementation, and so could be obtained as soon as a substantial portion of traffic is using RNAV.

The basic RNAV effect on enroute controller workload derives from the fact that a well-organized RNAV route structure reduces airspace conflict count in comparision to the present day VOR structure. As stated in Section 1.3, conflict count was reduced 26% by a transition to 100% RNAV. Reduced conflict counts are experienced also during the transition to a 100% RNAV environment. As before, these benefits are available independent of UG3RD implementation.

Two UG3RD program features are affected by RNAV in a manner as to reduce controller workload. As shown in Section 2.3, controller workload is reduced through the use of RNAV Metering and Spacing procedures in comparison to the radar vector M&S technique. The workload reduction results from a relaxation of the strict timing discipline inherent in the radar vector approach to M&S. The usage of 4D RNAV M&S procedures further reduces controller workload by eliminating one communication event per arrival.

The other UG3RD program so affected is the enroute metering concept. For enroute metering to function properly, considerable controller attention, with the aid of automated arrival time prediction, will be required for monitoring and modifying aircraft speeds such that the intended fix arrival time is made good within reasonable bounds. Usage of the 4D technique would eliminate that requirement, since arrival time control may be accomplished by the airborne system, as described in Section 2.3.4.

<u>Terminal Capacity and Delays</u> -- RNAV procedures have been shown, in a recent real-time simulation study summarized in Section 1.3, to produce a significant net increase in terminal arrival capacity, along with a corresponding reduction in delays. Arrival operations rates were shown to increase more that 3.2% (from 76.6 to 79.1 per hour) simply by switching all operations from radar vectors to RNAV procedures. This resulted in a sharp drop in total arrival time (time executing arrival procedures plus enroute holding time) of approximately 19% (from approximately 31 to 25 minutes per arrival). Such results depend only upon the implementation of RNAV, and are independent of any other UG3RD feature.

Terminal arrival capacity during IFR conditions may be increasable through the application of RNAV to define noise abatement approach profiles (ILS or narrow-beam MLS intercept). Using noise abatement approach procedures during low visibility conditions can increase IFR arrival rate since the most productive runways at an airport may be utilized, rather than others with lower capacity which have less-noise-sensitive straight-in approach aids. These routing techniques are discussed in Section 2.4 in more detail. (Note that RNAV noise-abatement routes, being STAR procedures, reduce controller workload under any conditions). These noise-abatement procedures could be implemented independent of other UG3RD programs.

In many cases, straight-in RNAV instrument approaches may be designed for many runways at airports where only circling approaches (or none at all) presently exist. This can improve operational reliability and hence reduce delays at those airports where lower minimums would result. Alternative RNAV approaches are discussed in detail in a VORTAC requirements analysis in Reference 8.

4D RNAV capability has been shown in several studies (see Section 2.3) to be able to improve the arrival time control capabilities of the Metering and Spacing technique. The annual benefit to be expected of such usage is summarized in Section 1.3.

Airspace Congestion -- Upon widespread implementation, RNAV could be utilized to reorganize holding airspace such that an increased number of arrival and enroute holding fixes would exist for serving the high delay airports. As discussed in Section 2.3, this could simplify delay techniques and flow control procedures as well as make more efficient use of airspace. This utilization is not predicated on any other UG3RD program.

Another possible method of enroute/arrival route airspace conservation would take advantage of the 4D RNAV capability as applied to the enroute metering concept. It may be possible (although it is yet to be demonstrated) to use the 4D function to allow a reduction to in-trail separation of arriving aircraft in the enroute/transition environment on a routine basis, resulting in higher utilization of available airspace. This would be accomplished by using time control to serve a "station-keeping" function. This would undoubtedly mean that some prior agreement must be reached as to the exact 4D algorithms to be used.

A final, but extremely significant, contributor to a resolution of the airspace congestion problem is the fact that the improvements to terminal capacity and delays due to RNAV will result in less congestion in the enroute and terminal airspace.

User Costs and Operational Convenience -- One of the important impacts of RNAV on user costs will be through the expected positive impact on terminal arrival delays. Operational convenience will be enhanced by reduced delays, RNAV noise abatement procedures, and RNAV approaches to small airports. None of these factors are predicated on other UG3RD programs.

The integration of RNAV procedures with the Intermittent Positive Control function, as discussed in Section 3.1, could enhance user acceptance of the IPC capability. The usage of RNAV IPC commands would, first, allow cockpit navigation (and therefore orientation) to be maintained during the avoidance maneuver, and second, facilitate the return to original track after the threat has passed (current IPC concepts are not concerned with that problem).

An area where significant user cost savings may be realized in terms of equipage costs for UG3RD features is due to the fact that a great deal of commonality exists between RNAV and MLS computational and display requirements. This would mean, as discussed in Section 2.4, that MLS capability could be provided simply as an add-on (receiver plus software modification) to existing or future RNAV systems. Future RNAV models could be designed specifically for MLS integration at a later date, considerably easing the MLS implementation and acceptance problem.

3.3.2 Areas of Interaction of RNAV and Other UG3RD Features

The subsections which follow deal with those areas where RNAV will duplicate, to some extent, the improvements to system performance measures which are expected of other UG3RD features. These improvements are in the following areas:

Controller Workload -- The dramatic reductions in controller workload, particularly in the terminal area, which should result upon the implementation of

RNAV are somewhat duplicative of the intended effect of the Control Message Automation Program. Of course, RNAV may be implemented well in advance of CMA, thus allowing an orderly progression of workload reduction. When CMA is implemented, the effect of RNAV on workload will probably be reduced.

Terminal Capacity and Delays -- Increased terminal arrival capacity achieved through the use of RNAV techniques duplicates, to some extent, the terminal capacity enhancements expected to result from the following programs:

- Metering and Spacing
- Wake Vortex Avoidance
- Microwave Landing System

As indicated in the M&S analysis discussed in Section 2.3, the RNAV arrival capacity payoff goes to zero when M&S is implemented, except in the 4D RNAV case where substantial capacity advantages are available. There is probably some degree of interaction between the capacity effects of WVAS and RNAV, although no data is presently available concerning the magnitude of the effect, or whether it is positive or negative. Reliable results could be obtained through real time simulation, but no such studies are at present planned.

In most situations the functional requirement of MLS to provide noise abatement approaches could be satisfied in the interim period by the RNAV/ILS intercept technique, provided that RNAV operations become commonplace before MLS is widely implemented. As presently configured, RNAV cannot substitute for, either in combination with ILS or not, the Category II/III capability of MLS, and so has no interaction with MLS with respect to that performance measure. It may be possible to maximize benefits while minimizing costs by combining the advantages of each; e.g. RNAV for area coverage combined with a narrow-beam ($\pm 10^\circ$) Category II/III MLS (this may involve an MLS configuration not presently contained in the submittal being made to ICAO). At airports which are not presently equipped with precision approach aids, RNAV can in many cases provide improved approach procedures at some of these airports. This advantage would diminish as airports are equipped with small community MLS configurations, and as GA operators equip with MLS avionics.

This discussion deals with those areas where RNAV can provide a compounded benefit, where RNAV itself can enhance the performance of an UG3RD feature. The following are examples of such cases; the presentation is brief since many have been mentioned earlier in a different context.

- IPC performance is improved through the use of RNAV, which maintains pilot orientation and allows course reacquisition

- 4D RNAV improves overall M&S system performance

- 4D RNAV can improve enroute metering system performance through providing higher fix delivery time accuracy, and (possibly) by increasing airspace utilization through station-keeping techniques.

- The user cost savings attributable to RNAV, and commonality with the airborne MLS computational requirement, will enhance overall acceptance of these UG3RD features.

3.3.3 Potential Effects of Enhancements to the RNAV Concept

Early studies of Area Navigation capabilities, traffic density projections and route width requirements indicated a need to improve RNAV accuracies significantly in order that route widths may be reduced. For example, the RNAV Task Force [38] specified reductions in route widths to ±2.5 nm (enroute) and ±1.5 nm (terminal) from existing widths of ±4 nm (plus 3.25° splay) and ±2 nm, respectively. The present widths are based upon minimum RNAV performance as specified by AC 90-45A [10]. Such accuracy levels would not support the reduced route widths specified in the Task Force report, and so revised, more stringent accuracy requirements are developed in that report. Subsequent analysis in a route width requirements study [2] and a terminal area route design study [9] has shown that these more stringent route width requirements are not really necessary to service the traffic density projected for the UG3RD time period. Therefore, the development of a more stringent (in terms of accuracy) performance requirement for RNAV would not be justified based upon route width criteria alone.

In order that 4D RNAV procedures may be introduced in the Metering and Spacing environment, however, it will probably be necessary to certify 4D RNAV systems as being capable of performing to a specified level of accuracy. This results since 4D control performance has implications in terms of aircraft separation, in this case longitudinal. Achieving the required accuracy should not be difficult, since such a high performance system could use the dual-DME/Air Data mode of navigation, which should result in performance much the same as that achieved in the airline quality system flight tests discussed in Section 2.3 and Appendix C. That system achieved, under terminal area conditions, an overall along-track error performance of 0.14 nm (1σ) (3.15 sec at 160 kt). It is quite feasible to require dual-DME navigation for 4D M&S, since nearly all potential M&S terminals are served by several nearby VORTACs, and since aircraft altitude at the approach gate is sufficient to insure reception in most cases.

One very significant result of the above considerations is that no improved VOR capability (PVOR) need be deployed to achieve this result. Therefore, implementation could be rapid, and at low ATC system cost.

If one presumes that such a RNAV performance specification (called Extended Capability RNAV) were to be established and accepted by industry, it is fruitful to evaluate other potential benefits which could be realized. AC 90-45A, and existing RNAV instrument approach procedure design requirements contained in TERPS [39], are based upon the minimal RNAV capability; i.e., low-cost nav receivers, single VOR/DME sensor, analog processing, no air data signal, etc. A new Extended Capability RNAV (ECR) specification could be created which would do little more than reflect the performance capabilities presently being demonstrated by the avionics industry, whereby high quality nav receivers, digital processing, and air data updating would be considered. This specification could set performance requirements individually for the single VOR/DME and multiple VOR/DME capability, with the latter applied to the 4D problem, and the former applied to designation of a new class of ECR instrument approach procedures. These ECR IAPs would allow considerably lower MDAs than can presently be obtained at most non-ILS locations with any non-precision approach aid. Thus, the gap between existing operational requirements at many smaller airports, and the promise of eventual MLS deployment, could be bridged effectively at most locations in a reasonably short time period.

It should be emphasized at this point that the Extended Capability RNAV concept does not depend upon deployment of any new, improved performance VOR/DME system. Rather, it would simply be an official recognition of the performance capabilities presently available and being demonstrated through the use of modern signal processing techniques.

As stated in Section 3.3.1, it may be possible to use 4D time control capability in the terminal transition environment under control of an enroute metering system as a tool to reduce longitudinal separations between aircraft in-trail on a route. This concept would utilize 4D to provide a relative station-keeping function through control of fix arrival time. The 4D accuracy requirement stated in an ECR specification would not be affected by this new function (excepting that the higher speeds involved may necessitate a larger allowable error value irrespective of navigation accuracy). However, it may be necessary to standardize the functioning of the time control algorithm in order to realize the needed value for longitudinal separation. The end result could be a significant improvement to the airspace saturation problem at busy airports.

3.4 SUMMARY OF RNAV IMPACTS ON THE OTHER UG3RD FEATURES

Present plans for UG3RD system implementation have been reviewed with the intention of determining, from a systems implementation viewpoint, where RNAV and the other UG3RD features may have an interaction. These results are based on an assumption that RNAV will be implemented at an early date, and in the following sequence:

1) Designation of a comprehensive high altitude RNAV route structure
2) Implementation of terminal RNAV routes and procedures at large hub airports
3) Implementation of terminal RNAV routes and procedures at large hub airports
4) Designation of a preliminary low altitude route structure
5) Eventual implementation of RNAV procedures at all towered airports
6) Eventual revision and expansion of the low altitude route structure

Preplanned direct flight plans would be allowed immediately, and granted whenever practicable. RNAV approach procedures would be designated as requests are received. Enroute resectoriztion would be completed when the majority of traffic are RNAV equipped (high and low altitude environments considered separately).

3.4.1 Implementation Interactions of RNAV and UG3RD Features

The following is a list of the UG3RD features including a brief discussion of the findings of this study relative to interactions with RNAV to be expected from an implementation viewpoint. The major motivating factors behind the development of each feature is stated. The first three items on the list relate to the MLS program. Mention is made of Category I, II and III MLS capabilities, while these have not yet been explicitly defined by ICAO. In these statements the "category" terms are intended to represent levels of MLS performance which would allow operations in visibility conditions of that category.

- MLS at Dense Terminals -- Wide Beam or (possibly) narrow-beam MLS will be installed at all major terminals so that Category II/III capability may be instituted, allowing improved operational reliability and reductions in weather-induced delays. It is assumed that a narrow-beam Category II/III MLS configuration could be made available, although this is not a currently-planned configuration.

- Wide-Beam MLS -- RNAV provides the area coverage capability in the terminal area to accurately navigate arrival routes and transitions to precision final approach guidance. As demonstrated in Appendix B, the RNAV capability can satisfy the noise abatement procedure requirements at many, but not all, terminals. Therefore, the wide-beam MLS implementation requirement could be eased; this might allow accelerated implementation of the basic and Category II/III narrow-beam configurations.

- MLS at Small Airports -- Category I, narrow-beam MLS capability is needed at airports where an operational requirement exists. This is particularly true where non-precision approach minimums are high, and where RNAV approach procedures will not adequately meet the operational requirement.

- DABS Surveillance -- The surveillance capability of DABS will be required for certain automation improvements and IPC. It is therefore an important UG3RD feature; however, DABS is not required to support RNAV.

- Intermittent Positive Control -- IPC is primarily intended for the VFR and mixed environments and will provide emergency separation service to non-controlled aircraft.

- Control Message Automation -- Significant reductions in ATC controller workload are expected to result as RNAV is introduced. The basic reasons are the usage of RNAV SID/STAR procedures, of RNAV with M&S, and of an enroute RNAV route structure. CMA (with DABS Data Link) is the major long-term UG3RD program intended for controller workload reduction. The beneficial aspects of RNAV in this area will help ease that problem until CMA is fully implemented.

- Near-Term Automation Enhancements -- Development of these enhancements (Conflict Alert, Conflict Probe, M&S, MSAW, etc.) is well under way. They primarily will improve safety and NAS/ARTS reliability.

- Metering & Spacing -- M&S should significantly improve capacity and reduce delays, and will also function well in an RNAV or mixed RNAV/radar vector environment, as demonstrated in detail in Appendix C.

- Enroute Metering -- This program should result in significant fuel savings.

- Central Flow Control -- Several UG3RD programs, such as M&S, WVAS, ASTC and RNAV, should produce significant airport and airspace capacity improvements, which should result in reductions to delay over the long term. RNAV terminal capacity improvements were demonstrated by real-time simulation [37]. These capacity improvements should help to ease the flow control problem.

- Airport Surface Traffic Control -- Since ground operations must continue during Category II/III conditions at airports where Category II/III landings are being conducted, ASTC improvements are needed, particularly as Category II/III capability becomes more widely implemented.

- Wake Vortex Avoidance -- WVAS is critical to improve terminal capacity and reduce delays. WVAS, RNAV, M&S and MLS Category II/III will work together to result in a very significant overall improvement to terminal capacity. RNAV capacity impacts are addressed in Section 2.3.1.

- Flight Service Station Modernization -- This program promises that a large potential cost savings will be available upon its successful completion.

It should be emphasized that none of these UG3RD programs are in any way necessary for the successful and beneficial implementation of RNAV as the primary navigation system.

3.4.2 Extended Capability RNAV Concept Impact

If the Extended Capability RNAV concept (ECR, Section 3.3.3) were adopted, the primary impact could be a significant redirection of the small airport MLS deployment program. Rather than serving as a primary Category I landing facility (a capability which ECR IAPs could substitute for at the lowest density airports), MLS would be implemented at specific locations where Category II capability is needed in addition to those larger airports for which it is already programmed. Extended Capability RNAV could significantly improve operational reliability at the many small airports wehre MLS is not envisioned to be installed.

4.0 OVERVIEW OF RNAV COSTS AND BENEFITS

The objective of this section is to derive and present the overall benefit-to-cost ratio expected to result from the implementation of area navigation. The cost and benefit data utilized herein are taken from earlier RNAV cost/benefit studies, particularly References 8 and 15, and to a lesser extent, References 6 and 37. Modifications to those costs and benefits which resulted from the present UG3RD impact study are also included. A limitation of the earlier RNAV economics studies (particularly 8 and 15) has been that while benefits at a particular point in time, and cumulative implementation costs, have been presented, the overall picture from years 1976 to 2000 was not analyzed. This section presents the results of a present-value benefit/cost analysis over that 25 year period according to the methods prescribed in OMB Circular A-94, Reference 43. This analysis is also based upon the latest aircraft activity projections, as prepared by the Office of Aviation Policy [1].

The methodology of the above-mentioned OMB circular is based upon the present value technique commonly used in financial analysis for investment decision-making. It allows various benefits and costs which accrue at different points in time to be analyzed and compared on an equivalent basis. This is done by adjusting all costs and benefits back to an equivalent present value through a formula which considers the value of the monetary resources involved. This formula is:

$$\text{Present Value} = (\text{Value n years later}) \text{ times } (1 + r)^{-n}$$

where "n" is the number of years passed before the cost or benefit will accrue, and "r" is the discount rate, or value of money (roughly equivalent to, but typically greater than, annual interest cost of money). The OMB circular specifies that a discount rate of 10% be used. The factor of inflation is not specifically accounted for by this formula. It is eliminated by expressing all future costs and benefits in terms of fixed (1976 in this case) dollars. Both costs and benefits are affected by inflation, and if the effect is approximately equal for both, inflation need not be explicitly considered. Fluctuations in costs different from the general trend of inflation are then included as parameters in the analysis, as are future fuel costs in the following analyses.

The overall intent of present value analysis is that, by presenting costs and benefits occuring at different times on an equivalent basis, rational investment decisions may be made based upon the resulting benefit/cost ratio. However, in order to be applied successfully, a logical scenario which describes the sequence of events relating to the subject investment decision must first be developed. The details of the scenario developed which describes the implementation of RNAV are presented in later subsections. However, the basic points are as follows:

- Phased implementation of RNAV in the sixty busiest hubs over seven years starting in 1982
- Equipage of the Air Carrier fleet over a four year period starting in 1982
- Availability of an enroute RNAV structure to users able to use it, starting in 1982

- Accommodation of 3D descent procedures starting in 1982

- Integration of 4D procedures with Metering & Spacing starting in 1985

This scenario presumes rapid adoption of RNAV by the major airspace users due to the large degree of payoff available. In the following sub-sections the present value costs and benefits to the airspace users, to the ATC system, and to air carrier passengers, as well as overall costs and benefits, are presented.

4.1 USER SCENARIO AND RESULTS

RNAV Equipage Costs

The air carrier fleet is projected to equip fairly rapidly once RNAV terminal procedures are instituted and an enroute route structure is made available. Most recent plans [44] indicate that initial capability will be available in 1982. Rapid equipage is anticipated for two reasons: (1) large RNAV payoff potential will motivate early equipage, particularly in view of high fuel costs, and (2) once started, airlines tend to equip a given aircraft type fleet with equivalent avionics quite rapidly in order to achieve uniformity, to ease training problems and to promote usage of optimum procedures. Since the busiest terminal hubs will institute RNAV first (see later terminal subsection), and since they will be dominated by wide body operations, wide bodies are projected in this scenario to initiate equipage first (1982) followed by regular-body aircraft (1983). A three year equipage period is projected for each. The resulting schedule, in terms of percentage or fraction of domestic fleet equipped, is listed in Table 4.1. Five aircraft type categories are used: four and three engine wide body types (4EWB, 3EWB), and four, three and two engine standard types (4ESB, 3ESB, 2ESB). Exceptions to the uniform three-year equipage schedule are as follows:

1) Three-engine wide body aircraft -- A certain number of DC-10's (National Airlines) are already equipped. This is reflected in the table.

2) Four-engine and two-engine standard body aircraft -- The numbers of these are projected to eventually decline (see Table 4.2). To avoid uneconomical equipage, the 1985 target was set to 100% of the 1990 fleet rather than 100% of the 1985 fleet, as was done for the three-engine standard body aircraft.

The total air carrier fleet complement projection over the twenty-five year period was provided by the Office of Aviation Policy [1], and is shown in Table 4.2. However, this data represents total U.S. fleet complement, including those involved in international as well as domestic operations. Since area navigation is considered as a domestic navigation system, it is necessary to estimate the fleet complement involved principally in domestic operations. In order to obtain a basis for such a projection, the most recent Civil Aeronautics Board cost and performance data was reviewed (Reference 45). From this data it was determined that the U.S. Air Carrier Fleet in 1975 was operated according to the breakdown in Table 4.3.

Table 4.1 Per Cent Equipage of the Air Carrier Fleet

Year	4EWB	3EWB	4ESB	3ESB	2ESB
1976	0.0%	5.0%	0.0%	0.0%	0.0%
		4.6			
		4.2			
		3.8			
1980		3.4			
	0.0	3.0			
	33.3	35.3	0.0	0.0	0.0
	66.7	67.7	22.0	33.3	30.3
	100.0	100.0	44.0	66.7	60.7
1985			66.0	100.0	91.0
			72.8		92.8
			79.6		94.6
			86.4		96.4
			93.2		98.2
1990			100.0		100.0
1995					
2000	100.0	100.0	100.0	100.0	100.0

Table 4.2 Projected Air Carrier Fleet [1]

Year	4EWB	3EWB	4ESB	3ESB	2ESB
1975	105	179	522	747	541
1980	160	275	455	959	720
1985	260	475	365	1498	640
1990	410	903	240	1570	582
1995	530	1515	155	1447	520
2000	650	2020	60	1416	460

Table 4.3 1975 Average U.S. Air Carrier Fleet [45]

Aircraft Type	4EWB	3EWB	4ESB	3ESB	2ESB
Total A/C	92.4	177.7	468.0	728.0	486.2
Domestic A/C	40.5	158.8	283.4	689.5	465.2
Domestic %	43.8	89.4	60.6	94.7	95.7

The figures in Table 4.3 are averages for the year, thus yielding fractional aircraft counts. The aircraft type categories represent four-engine wide body, three-engine wide body, four-engine standard body, etc., the same as in Tables 4.1 and 4.2. Under ordinary circumstances, this set of data representing domestic proportion would be carried through as a projection for the next twenty-five years. However, a review of the fleet mix projection (Table 4.2) indicates that perhaps some better assumptions may be made. A projection was thus made based on the following assumptions:

- The proportion of domestic seats available from all four-engine as opposed to all three-engine aircraft will remain constant.
- Since 4ESB aircraft are no longer being manufactured, and a certain number are equipped for international operations, the 4ESB domestic fraction will remain fixed.
- Three-engine standard body aircraft will be manufactured primarily for the domestic market, thus the total non-domestic 3ESB count was presumed to be constant.
- The 2ESB domestic fraction is assumed to remain fixed.

The resulting breakdown of domestic fleet percentages over the next twenty-five years is given in Table 4.4. The total count of aircraft to be equipped in any given year is therefore the product of aircraft fleet count, domestic fraction, and fraction RNAV equipped (Tables 4.2, 4.4 and 4.1). These values are utilized in the assessment of both equipage and maintenance costs and in ascribing user benefits as is done in later sections.

Table 4.4 Air Carrier Fleet Domestic Fraction

Year	4EWB	3EWB	4ESB	3ESB	2ESB
1975	.438	.894	.606	.947	.957
1980	.487	.878	.606	.960	.957
1985	.519	.861	.606	.974	.957
1990	.538	.891	.606	.975	.957
1995	.544	.909	.606	.973	.957
2000	.549	.914	.606	.973	.957

It is necessary to estimate the costs which an airline will incur in equipping each aircraft of a given type, and the recurring costs of maintenance and data base update, in order to fully assess RNAV equipage costs. Certain data is available since avionics manufacturers have already produced such equipment commercially to a limited extent. However, costs of installation include several factors over and above avionics unit costs. Included are aircraft rewiring and idle time, spare parts inventory, and crew/maintenance training. Recurring annual costs include routine maintenance and data services. Previously [8] avionics manufacturers were queried in order to obtain estimates of these factors. These results have been updated during the present study through discussions with Delco, Collins Radio Group and National Airlines [46]. While most of the costs could not be defined absolutely, estimates were made as follows:

1) RNAV Cost - $40K each (ARINC MK13), $110K each (ANS-70)
2) Spares Inv. - 25%
3) Installation - $50K per aircraft
(would vary widely based on system complexity and aircraft layout)
4) Training - small
5) Annual Maintenance - $0.35/flt. hr. (MK13)
6) Data Services - $0.35/flt. hr. (MK13)

The RNAV system considered was the basic airline ARINC MK13 with Flight Data Storage Unit. Because wide body aircraft would experience greater benefits due to RNAV, a more complex and sophisticated system was postulated (similar to the Collins ANS-70, for example), and the various cost categories were increased accordingly. The training costs listed are estimates. Maintenance cost for the ANS-70 was increased in proportion to system cost. Data services costs were also increased, but not as much since the amount of data is fixed. Costs actually used in this analysis are presented in Table 4.5. These represent costs for a typical dual installation. Note that it is not necessary to equip the wide body aircraft with the more sophisticated type system in order to get RNAV benefits.

Table 4.5 Airline RNAV Equipage Costs

Category	Wide Body	Standard Body
Purchase	$110K x 2	$40K x 2
Spares	55K	20K
Installation	60K	40K
Training	5K	3K
TOTAL ACQUISITION	$340K	$143K
Maintenance	$ 3K x 2	$ 1K x 2
Data Services	2K x 2	1K x 2
TOTAL ANNUAL	$ 10K	$ 4K

The results of this cost analysis show that, over a twenty-five year period, a total of $1436 million would be spent (at 1976 dollars) on equipment, installation and maintenance. The equivalent present value in 1976 of these expenditures at a 10% annual discount rate is $442 million. This is the value which will be compared to present value airline benefits in order to determine benefit/cost ratio. The overall airline cost results are presented in Table 4.6. In Appendix F detailed airline cost results are presented. Annual cost results are stated for each aircraft category.

Table 4.6 Airline Equipage Total Dollar Costs and Present Value Costs

A/C Type	4EWB	3EWB	4ESB	3ESB	2ESB	Total
Avionics	$ 78.3M	$406.3M	$ 12.2M	$122.5M	$ 44.6M	$663.9M
Installation, etc.	42.7M	221.6M	9.6M	96.4M	35.1M	405.5M
TOTAL CAPITAL	$121.1M	$628.0M	$ 21.7M	$218.9M	$ 79.8M	$1069.4M
Maintenance, etc.	$ 41.0M	$184.4M	$ 7.7M	$ 98.3M	$ 35.3M	$366.8M
TOTAL	$162.1M	$812.4M	$ 29.4M	$317.2M	$115.1M	$1436.2M
1976 Present Value	$ 49.1M	$210.5M	$ 12.3M	$123.9M	$ 46.3M	$442.2M

The remaining RNAV equipage costs to be considered concern general aviation equipage. It is of interest to note that RNAV has been well accepted by the GA population. Many thousands of units (mostly low-cost single waypoint models) have been sold. However, it is much more difficult than in the airline case for purposes of the present analysis to determine GA RNAV equipage costs and benefits, since no direct data representing those operators who would equip to take advantage of RNAV terminal procedures and route structures is available. In the air carrier case, with the exception of high-time airframes, all aircraft could be presumed to become equipped since there is a large payoff potential. GA payoff is smaller and more difficult to demonstrate in terms of direct dollar savings. Obviously, there are other non-quantifiable benefits which motivate GA operators, as demonstrated by the number of units sold to date. In order to simplify this analysis and achieve a conservative result, the following approach was taken: Equipage costs for those GA operators most likely to utilize RNAV to get dollar benefits have been computed, and will be added to the total of RNAV present value costs. Although dollar benefits for GA users can, and have [8] been demonstrated, none are presented here since the data base required for their computation over a twenty-five year time period is not available. This will mean that the overall RNAV benefit/cost result will be quite conservatively expressed.

For purposes of this analysis, those GA users presumed to equip are as follows:

1) All high altitude operators (turbine aircraft), since they can get a significant enroute benefit.

2) All piston operators who base their aircraft at one of the high or medium density hub airports, since they too may potentially derive a benefit.

All of these have been assumed to initiate equipage in 1982, with all candidate aircraft equipped within five years. The projections of eligible aircraft counts were taken from the AVP study [1]. Aircraft currently based at the high and medium density hubs were determined in an earlier study [8] from FAA aircraft registration files. The extrapolations used in this study were not linear, but imposed limits upon the numbers of GA aircraft expected to be based at the high and medium density hubs. These limits are expected to result from the eventual domination of these airports by air carrier operations, as shown in the traffic projections supplied by AVP [1]. As a result, single engine piston aircraft based at large and medium hubs are assumed to remain constant at 1975 levels, while multiengine piston aircraft are assumed to be limited at the extrapolated 1980 level. These projection data are listed in Table 4.7.

Table 4.7 RNAV-Equipped GA Aircraft Projections

Projection Year	1975	1980	1985	1990	1995	2000
All Piston-Single	131,687	149,990	181,803	224,139	276,096	339,848
All Piston-Multi	20,123	25,610	33,714	44,998	59,840	79,326
All Turbine	4,005	6,615	9,843	14,450	20,811	29,345
RNAV Piston-Single	-0-	-0-	3,966	4,958	4,958	4,958
RNAV Piston-Multi	-0-	-0-	1,659	2,074	2,074	2,074
RNAV Turbine	-0-	-0-	7,099	14,450	20,811	29,345

From the earlier cost study [8], an average RNAV equipage cost for each aircraft category may be derived. These values include not only RNAV equipment cost, but also the fact that certain aircraft will require other equipment. For example, many of these GA aircraft would not ordinarily be equipped with DME, which is required for RNAV operation. These resulting average equipage costs are listed in Table 4.8, which shows total equipage costs, 1976 present value costs, and total and present value maintenance costs, presuming an annual 4% maintenance cost rate.

Table 4.8 Equipage Total Dollar Costs and Present Value Costs

Aircraft Category	Piston-Single	Piston-Multi	Turbine	Total
Avionics Cost per A/C	$ 3901	$ 4890	$ 7125	---
Maintenance Cost per A/C	156/yr	196/yr	285/yr	---
Total Avionics Cost	19.341M	10.142M	209.083M	$238.566M
Total Maintenance Cost	13.152M	6.896M	86.389M	106.437M
Total Cost	32.493M	17.038M	295.472M	345.003M
1976 Present Value Cost	$12.325M	$ 6.463M	$ 76.400M	$ 95.188M

Terminal Area Airline Benefits

User terminal area benefits were projected over the twenty-five year period for air carrier operators from two primary data sources. First, previous analyses [8] have quantified the benefits which will become available to air carrier operators at major terminal areas. Second, the Office of Aviation Policy [1] has provided detailed projections of both operations counts at the major terminals and of the distribution of operations by aircraft category at each individual terminal. These data coupled with the RNAV equipage schedule (see Table 4.1) are combined to determine annual benefits for each year from 1982 through 2000, and the total present value benefit.

The operations projection data from Reference 1 are illustrated in Table 4.9. The items provided which are of interest are total itinerant operations and air carrier itinerant operations, plus the air carrier fleet participation at that airport by aircraft group for each year given. In the earlier study [8] a few major terminals were studied (EWR, JFK, LGA, PHL, DEN, SFO, MIA, MSY, ORD), and RNAV benefits in terms of fuel and time savings for each aircraft type were computed. In that study a procedure for extrapolating benefits to other airports was developed, which was based on a traffic count parameter. The parameter used was the remainder after general aviation itinerant operations are subtracted from air carrier itinerant operations, which results in a measure of air carrier dominance at the terminal. Since the GA itinerant parameter was not provided in the AVP data, a new method of extrapolation was developed so that benefits could be estimated at many more airports than the nine which were studied in detail. In this case, as in the earlier study, the extrapolation equation was developed through regression analysis. The operations count data source used in Reference 8 and the current study for the regression analysis is "FAA Air Traffic Activity, CY1974 ", Reference 47. Various combinations of those data items from Reference 47 which are also available in the AVP traffic projections [1], and which represent in some way the measure of air carrier traffic dominance, were tried in order to find a substitute extrapolation relationship. A measure, root-mean-square error of the curve-fit estimate, was used to evaluate the

Table 4.9 Terminal Projection Data [1] -- Denver

YEAR	1975	1980	1985	1990	1995	2000
Air Carrier Opns.	203000	249000	295000	341000	377000	377000
Itinerant Opns.	372000	442000	493000	500000	500000	500000
Total Opns.	397000	464000	498000	500000	500000	500000
4EWB %	1	1	2	3	4	6
3EWB %	7	11	15	19	22	26
4ESB %	9	3	-	-	-	-
3ESB %	44	45	42	37	40	42
2ESB %	23	31	41	41	34	26

quality of the resulting curve-fit relationship in each case. The parameter finally settled upon as the extrapolation variable was the ratio of air carrier operations to total itinerant operations. Use of this ratio parameter actually resulted in a lower root-mean-square error than the parameter used in the earlier study [8], which was air carrier operations minus GA itinerant operations. The resulting errors are stated in Table 4.10.

Table 4.10 Regression Fit Root-Mean-Square Error Comparison (Fuel-Pounds, Time-Minutes)

Aircraft Category	4EWB		3EWB		4ESB		3ESB		2ESB	
Fit Parameter:	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time
Air Carrier-GA Itin. [8]	48.4	.090	24.5	.082	5.9	.074	10.3	.076	14.4	.075
Air Carrier/Total Itin.	24.2	.037	17.2	.033	14.8	.013	6.4	.039	13.9	.044

The regression curve fits were applied to the traffic projections for all of the sixty large and medium hub airports identified in Reference 8, except for EWR, LGA, JFK and ORD. As discussed in that report, these are highly special cases which do not conform with the results obtained for the more ordinary terminals. Therefore, the raw results of the RNAV benefits analysis were used directly, rather than the curve-fit data, for those four airports.

As a part of this task it was necessary to project the timing and order in which RNAV procedures would be established at the high and medium density hub airports. Since the establishment of RNAV procedures will involve airspace restructuring, route design and analysis, procedure definition and controller education, they cannot all be implemented at one time, but will be phased in. A schedule for implementation was developed, which is listed in Table 4.11. Basically, the airports are implemented in order of decreasing share of total U.S. enplanements, as obtained from Reference 48. The purpose is to cause most airports with significantly large traffic volumes to have RNAV procedures by 1984.

The procedure used to project RNAV benefits for any given year is as follows: First, those airports which would have RNAV procedures are identified from Table 4.11. Then, for a given airport, the traffic demand data for the year in question would be taken from a table for the airport (like Table 4.9), using interpolation where necessary. Number of operations for each aircraft category

Table 4.11 RNAV Terminal Implementation Schedule (High and Medium Density Hubs)

Implementation Year	Share of U.S. Enplanements	Airports
1982	>5.0%	NY (EWR,LGA,JFK), ORD, ATL, LAX
1983	>2.5%	DEN, MIA, SFO, BOS, DFW, DCA, IAD, FLL
1984	>1.0%	MSY, PHL, CLE, DTW, IAH, PIT, STL, MCI, MSP, TPA, SEA, LAS
1985	>0.65%	CVG, MCO, PDX, MEM, PHX, SAN, BAL
1986	>0.50%	BDL, BUF, IND, CLT, MKE, SLC, CMH
1987	>0.35%	JAX, SDF, SAT, ABQ, DAY, BNA, ORF, OKC, OMA, ROC, SYR
1988	<0.35%	SMF, ALB, BHM, DSM, ELP, TYS, PVD, RDU, TUL

would be generated from the fleet mix data (again, Table 4.9). The per operation benefit would be derived from the regression equations for that aircraft type. The air carrier fleet equipage schedule (Table 4.1) would then be consulted to determine the percent of that aircraft category which are RNAV equipped and so would get benefits. Thus the total benefits for that aircraft category, and the total for that airport, may be computed.

In order to express these terminal area fuel and time benefits in dollar terms, values for fuel cost and aircraft direct operating cost (less fuel) per hour must be estimated. Historic data describing these costs is available from the Civil Aeronautics Board (Reference 45) for 1975 and earlier years. However, appropriate values for future benefits evaluation are not easily defined. First of all, the future price of fuel is subject to much speculation. Secondly, different air carriers will treat the value of aircraft time differently, including or discarding various items in the direct operating cost formula. Therefore, for purposes of these analyses, two different sets of fuel/time cost levels will be used in an effort to bound the expected degree of benefit in a realistic manner. From [45], the average 1975 fuel cost was about 28¢ per gallon, while published reports indicate that it is closer to 30¢ per gallon this year. Therefore, a fuel price range of 24¢ to 36¢ per gallon was used for this study. The two aircraft time cost levels were defined as follows: The high cost was determined by subtracting fuel costs from total hourly direct operating costs, using the 1975 CAB data [45]. The low time cost was derived by subtracting depreciation and rentals as well as fuel cost from total hourly DOC, and then further reducing the remainder 20%. The resulting aircraft time cost values are given in Table 4.12.

Table 4.12 Aircraft Hourly Cost Values Used in Projections

Category	4EWB	3EWB	4ESB	3ESB	2ESB
High (DOC less Fuel)	$1810	$1307	$773	$612	$544
Low (less Dep. + Rentals + 20%)	899	648	484	370	343

The summary results of the airline terminal benefits analysis are presented in Table 4.13. The total dollar value of benefits accumlated over the years from 1982 to 2000 are listed for each aircraft category. Also, the present value (1976) of the benefits is listed. Appendix F lists the detailed benefit data on a year-by-year basis.

Table 4.13 Overall Air Carrier Terminal RNAV Benefits, 1982-2000

	4EWB	3EWB	4ESB	3ESB	2ESB	TOTAL
Fuel Savings (gal)	636M	923M	44M	862M	507M	3022M
Time Savings (hr)	204K	440K	23K	683K	494K	1844K
Total Dollar Value:						
Low Cost Assumption	$348M	$507M	$22M	$460M	$291M	$1627M
High Cost Assumption	616M	908M	34M	728M	451M	2738M
1976 Present Value:						
Low Cost Assumption	$ 76M	$112M	$ 7M	$105M	$ 70M	$ 371M
High Cost Assumption	134M	201M	12M	167M	108M	622M

Enroute Airline Benefits

This section describes the basic method by which the enroute route length benefit to high altitude users was projected over the years from 1982 to 2000. The enroute route length benefit has been determined to be 1.61% in Reference 8. This was estimated by comparing an experimental RNAV route structure to the existing VOR structure, and expressing the distance savings in terms of a percent of enroute distance (stage length less terminal radius). The enroute analysis was based upon a comparison of the present jet route structure with a candidate RNAV route structure which was developed specifically for purposes of analysis. In the analysis, route length benefits were computed for each of more than 400 city pairs. These were then aggregated based on airline demand for each city pair. Also considered were the effects which restricted areas have on present as well as RNAV routings. Weather considerations were factored in through analysis of available routes and preferences based on minimum flight times considering wind conditions. In order to project benefits for any given year, the number of operations and average stage length for each aircraft category must be known. The basic data sources used for this study were the projected air carrier fleet mix (Table 4.2) from [1], the projection of domestic fleet fractions described earlier (see Table 4.4), the air carrier fleet equipage schedule (Table 4.1) and historic operations and stage length data from the CAB [45]. Reference 1 did not provide annual operations count and stage length on an aircraft category basis, necessitating the usage of historic data.

The 1975 CAB statistics [45] were analyzed in order to determine the average annual number of departures performed per aircraft by each category of aircraft in domestic operations. Also, the average domestic stage length for each category was computed. The resulting data are stated in Table 4.14.

Table 4.14 Domestic Departures and Stage Length [45]

	4EWB	3EWB	4ESB	3ESB	2ESB
Domestic Departures	823.4	1238.4	1341.3	2104.5	3200.9
Average Stage Length	1796.	1012.	930.	523.	289.

The enroute portion of the flight in each case was estimated by subtracting ninety miles from the stage length to account for origin and departure airport radii. The resulting enroute distance was multiplied by 1.61%, by the number of departures and by the number of domestic aircraft scheduled to be equipped for a given year to get enroute distance saved for that aircraft type for that year. To convert distance saved to fuel and time quantities, average enroute speed and fuel consumption must be known. Values for these items were derived from aircraft performance handbooks at cruise altitude under nominal conditions, as described in Reference 9. The per mile fuel and time consumption rates used are stated in Table 4.15. The overall fuel, time and cost savings results are summarized in Table 4.16. Detailed year-by-year results are listed in Appendix F.

Table 4.15 Aircraft Fuel and Time Per Mile (enroute)

	4EWB	3EWB	4ESB	3ESB	2ESB
Fuel Consumption (lb)	46.7	32.0	26.4	18.0	12.8
Time (min)	0.1231	0.1252	0.1294	0.1279	0.1328

Table 4.16 Overall Air Carrier Enroute RNAV Benefits, 1982-2000

	4EWB	3EWB	4ESB	3ESB	2ESB	TOTAL
Fuel Savings (gal)	701M	1692M	144M	1014M	181M	3732M
Time Savings (hr)	197K	705K	75K	767K	200K	1945K
Total Dollar Value:						
Low Cost Assumption	$346M	$ 863M	$ 71M	$ 527M	$112M	$1919M
High Cost Assumption	610M	1531M	110M	834M	174M	3259M
1976 Present Value:						
Low Cost Assumption	$ 75M	$ 173M	$ 20M	$ 129M	$ 28M	$ 425M
High Cost Assumption	133M	307M	30M	204M	44M	718M

Airline VNAV Descent Benefits

Descent procedures have been under study by airlines in recent years as a result of the fuel conservation potential available through improvements in procedures. The objective is to initiate a standard descent from cruise altitude at the last possible moment which will insure arrival at the point prescribed by ATC at the required altitude. This may be approximated through the use of various procedures and flight planning aids; however, VNAV techniques should provide more accurate control of descent initiation point, and result in a net savings in fuel and time. In Reference 8 VNAV descents were analyzed in detail in order to quantify the degree of benefit to be expected per descent operation. The results are presented in Table 4.17. They were derived from an analysis of the nine airports studied in determining terminal RNAV benefits.

Table 4.17 VNAV Savings per Descent Operation [8]

	4EWB	3EWB	4ESB	3ESB	2ESB
Fuel (lb)	56.7	55.8	81.3	44.7	49.9
Time (min)	0.132	0.239	0.340	0.305	0.459

The determination of overall VNAV descent benefits for the years 1982-2000 was accomplished in much the same manner as the enroute route length benefits analysis, since the same data sources are required. Once the number of aircraft departures for each aircraft category has been calculated, it is multiplied by the descent benefit values. The overall results are presented in Table 4.18. Detailed year-by-year results are listed in Appendix F.

Table 4.18 Overall Air Carrier VNAV Descent Benefits, 1982-2000

	4EWB	3EWB	4ESB	3ESB	2ESB	TOTAL
Fuel Savings (gal)	31M	199M	33M	360M	221M	843M
Time Savings (hr)	8K	91K	15K	262K	216K	592K
Total Dollar Value:						
Low Cost Assumption	$14M	$106M	$15M	$184M	$127M	$447M
High Cost Assumption	25M	190M	23M	290M	197M	726M
1976 Present Value:						
Low Cost Assumption	$ 3M	$ 21M	$ 4M	$ 45M	$ 32M	$105M
High Cost Assumption	5M	38M	6M	71M	50M	170M

Airline 4D RNAV Benefits

The usage of area navigation equipment to provide accurate time-of-arrival control (called 4D RNAV) in the context of a Metering and Spacing (M&S) environment has been shown (see Section 2.3) to have the potential for improving the ability of M&S to space aircraft, and therefore to reduce arrival delays. In an earlier effort to quantify the delay-reducing impact to be expected (Reference 8), a simulation technique was utilized to predict arrival delays in an M&S environment in the mid-1980's. This simulation technique utilized a model of airport operations which considered the following factors:

- The arrival aircraft traffic demand pattern (hourly) typical of a given airport
- The aircraft type mix pertinent to the airport
- The in-trail minimum separation requirements for each type of aircraft in use (3/4/5 mile separation criteria in effect at that time)
- Typical approach speeds of each aircraft type
- Expected manual, M&S and 4D M&S ATC performance capabilities anticipated (discussed below)
- Actual historic demand/delay data for the airport, for model calibration

Delay conditions at eight airports (ORD, JFK, LGA, EWR, PHL, MIA, DEN, SFO) were analyzed, and the results were extrapolated over a total of twenty-four airports which are logical candidates for 4D procedures. In that study the delivery accuracies determined to be representative of automated M&S and of 4D M&S systems were 11sec. and 5 sec. respectively (1σ), and the 4D benefits estimation was taken as the difference in the amount of delay which resulted. It is the conclusion of this study (Section

2.3) that the automated M&S system should be capable of a delivery accuracy of 8 sec. rather than 11 sec. The net effect of this improved M&S capability of concern here would be a reduction in the degree of benefit resulting from the usage of the 4D capability. However, this benefit would still be substantial.

The approach used in projecting benefits to the year 2000 was to first re-evaluate expected benefits per operation at the twenty-four domestic high delay airports (based on the 8 sec. accuracy) for the year 1985, and then to project these over all RNAV operations at those airports for the remaining years in a manner similar to that used in the analysis of terminal area benefits, described earlier. The reevaluation of benefits was performed by recomputing delay conditions at the eight primary airports based on the eight second M&S accuracy, and extrapolating the results to the remaining sixteen terminals. The results of this extrapolation are presented in Table 4.19, which may be compared with Table 3.29 in Reference 8. These results were based upon the traffic demand projected for 1985, which was taken to be the initial year 4D operations would be implemented. That implementation date was chosen for two reasons: to allow time for the development of M&S systems which are 4D RNAV-compatible, and since 1985 is the first year where nearly all airline operators would be RNAV-equipped, therefore allowing the maximum benefit from 4D to be realized.

Operations rates at most of the twenty-four airports considered are projected to increase after 1985. It could therefore be presumed that delays, and so the 4D RNAV benefit, would also increase. However, such an increase in 4D benefit is not reflected in the results presented below. The reasoning is that there are several factors which should act to reduce delays, or act to slow the growth of delays, over this time period. Several of these factors are features of the Upgraded Third Generation System. Therefore, it is difficult to anticipate the exact trend of delays at such distant points in time. For purposes of projecting benefits to the year 2000, per-aircraft 4D benefit has been taken to remain constant at the 1985 level, even though traffic is projected to increase dramatically. It is anticipated that this entire 4D benefit estimation process will be refined in a subsequent task of this RNAV technical support task order contract.

The 4D RNAV benefits projection was performed by multiplying the delay time savings given in Table 4.19 by the traffic projections at each of the airports. Results are expressed on an aircraft category basis by considering the demand-mix data for each airport (see Table 4.9), and the fleet equipage projection (Table 4.1). It was also necessary to estimate the fuel savings which would accompany the delay time savings. Fuel consumption in each aircraft category was determined from aircraft performance handbooks. The data used was at a standard holding condition at 10,000 ft. at 210 KIAS. The resulting data is shown in Table 4.20. Overall fuel, time and dollar savings are shown in Table 4.21. Detailed year by year savings data are listed in Appendix F.

Table 4.19 1985 Airline Per Operation Delay Savings

Airport	Daily Itinerant Arrivals	4D Savings per Operation (min)
ORD	908	2.00
ATL	830	1.63
JFK	567	1.79
LGA	503	1.28
SFO	542	1.57
LAX	670	3.02
DEN	404	0.77
PHL	296	0.44
EWR	264	0.37
MIA	455	1.01
DFW	563	1.75
DCA	315	0.48
PIT	362	0.62
BOS	404	0.77
CLE	247	0.34
DTW	326	0.51
MSY	174	0.23
LAS	200	0.26
STL	358	0.61
FLL	133	0.18
TPA	196	0.26
MSP	242	0.33
SEA	216	0.28
BAL	141	0.20

Table 4.20 Holding Fuel Flow

Aircraft Category	Weight (Klb)	Fuel Flow (lb/min)
4EWB	400	245.3
3EWB	260	170.9
4ESB	180	148.1
3ESB	110	100.0
2ESB	70	66.4

Table 4.21 Overall Air Carrier 4D RNAV Benefits, 1985-2000

	4EWB	3EWB	4ESB	3ESB	2ESB	TOTAL
Fuel Savings (gal)	600M	923M	46M	833M	371M	2774M
Time Savings (hr)	261K	576K	33K	889K	596K	2355K
Total Dollar Value:						
Low Cost Assumption	$379M	$ 595M	$27M	$529M	$294M	$1823M
High Cost Assumption	688M	1086M	42M	844M	458M	3118M
1976 Present Value:						
Low Cost Assumption	$ 78M	$ 126M	$ 9M	$118M	$ 70M	$ 401M
High Cost Assumption	142M	229M	14M	188M	109M	683M

4.2 ATC BENEFITS AND COSTS

Terminal VOR Maintenance Savings

In Reference 8, a detailed study was made of high and medium density terminal areas in an effort to determine whether low altitude and terminal VOR and VORTAC stations may be removed, given that RNAV operations come to predominate the area. The study considered not only the requirement for area coverage VORTACs as opposed to point-to-point VOR route coverage, but also provision of non-precision approaches to satellite airports within the terminal area boundaries (45 or 60 nm, depending upon area complexity). It was found that in those terminals where four or more VORs currently exist, forty percent of the stations could be removed, resulting in a savings of thirty-two stations in the twenty high density terminal areas, plus sixteen more in the thirty-four medium density terminal areas. Low density areas were not studied. Removal of these stations would result in several types of cost savings: maintenance costs, improved land usage (or disposal), elimination of need for upgrading equipment, etc. In this projection of ATC cost savings, only the maintenance savings were considered; the conservative assumption that land value and station salvage value would compensate decommissioning costs was made. The annual VORTAC maintenance cost which would be saved per station decommissioned would be $48,500 [8]. This figure is based on an assumption that all stations are equipped with dual VOR/TACAN equipment for sake of redundancy. In actual fact, at present, 85% of VORs are dual and 56% of TACANs are dual, so the actual maintenance costs (and therefore RNAV benefits) may be somewhat lower than stated.

To establish a schedule for station removal, the schedule for terminal RNAV implementation, Table 4.11, was used. The numbers of stations to be removed each year are listed, along with annual savings, in Table 4.22. Note that no stations are removed until 1985, to allow users to equip such that the RNAV area coverage may be utilized.

Table 4.22 VORTAC Decommission Savings, 1985-2000

Year	Stations Removed	Savings
1985	36	$1746K
1986	5	1989K
1987	2	2086K
1988	5	2328K
1989	0	2328K
•	•	•
•	•	•
•	•	•
2000	0	2328K
TOTAL	48	$36,084K
1976 PV Savings		$ 8,034K

Terminal Controller Productivity Savings

Earlier studies [49, 15] have investigated terminal and enroute ATC controller productivity and the improvements to controller workload which can result from the implementation of RNAV as the major navigation system. These studies have

indicated that, when RNAV is fully implemented, overall controller productivity improvements of 10% (terminal) and 14% (enroute centers) will result. In order to interpret what these results mean in terms of savings in staff salaries and benefits, it is necessary to have estimates of staffing levels over the next twenty-five years. It is also necessary that such estimates reflect the productivity improvements which will result from other UG3RD features so as to not overestimate the RNAV savings. Furthermore, any effect of UG3RD features on RNAV percent contribution must be recognized.

A study has been performed (Reference 50) wherein overall staffing levels to the year 2000, given that the UG3RD is implemented, are projected. This study presumed the implementation of UG3RD would occur basically in two phases with the latter phase, which includes Control Message Automation, to occur beginning in 1985. A review of the UG3RD features has shown that most of the features will not significantly affect the ability of RNAV to reduce controller workload. However, Control Message Automation, by drastically reducing communications workload, may have the effect of diminishing the ability of RNAV to further reduce workload. Since there is no significant analytical or simulation data available under these conditions, the resultant effect must be estimated. To be on the conservative side, it is assumed herein that the controller productivity improvement attributable to RNAV is reduce 50% when CMA is implemented.

To compute the RNAV impact on terminal controller staffing levels at the twenty-six cities studied in [50], the RNAV implementation schedule in Table 4.11 was utilized, along with the projected staffing levels given in [50]. Thus, RNAV savings will phase-in as RNAV implementation proceeds. CMA was presumed to be initially started in 1985 and phased-in through 1990. The resulting staff position savings due to RNAV are listed in Table 4.23 along with total savings to year 2000, using the annual value of $24,795 for controller salary plus benefits from that reference.

Table 4.23 Terminal Area RNAV Staff Savings, 1982-2000

Year	Staff Required without RNAV	RNAV Savings
1982	1330	34
1983	1311	64
1984	1294	115
1985	1279	107
1986	1198	94
1987	1113	76
1988	1023	58
1989	931	38
1990	834	39
1991	847	40
1992	860	41
1993	873	42
1994	886	43
1995	899	44
1996	907	44
1997	916	45
1998	924	46
1999	933	46
2000	941	47
TOTAL SAVINGS		1063 Man-Years $26.4M
1976 PV Savings		$ 8.0M

Enroute Controller Productivity Savings

In Reference 50, the future staffing level impact of the UG3RD for the twenty enroute centers was projected to the year 2000. The impact of RNAV in the enroute environment has been estimated to be 14%, as stated earlier. Control Message Automation was projected in that reference to be implemented enroute in 1989 and 1990. As before, CMA is presumed (conservatively) to reduce the RNAV benefit by 50%, to a 7% productivity improvement. The resulting projected staffing levels, and the RNAV savings, are listed in Table 4.24. It should be noted that, if CMA were not to be implemented, or were to be delayed, the total RNAV savings would be much greater.

Table 4.24 Enroute RNAV Staff Savings, 1982-1999

Year	Staff Required without RNAV	RNAV Savings
1982	10574	370
1983	8961	627
1984	9167	962
1985	9373	1312
1986	9682	1355
1987	11021	1543
1988	11948	1788
1989	10712	1168
1990	9476	663
1991	9785	685
1992	10094	676
1993	10506	735
1994	10918	764
1995	11330	793
1996	11948	836
1997	12566	880
1998	13081	916
1999	13493	945
TOTAL SAVINGS		17018 $422.0M
1976 PV Savings		$120.7M

Enroute VORTAC Costs

In Reference 8, a detailed study of VORTAC requirements for enroute coverage is documented. In that study it was found that the high altitude RNAV route structure could be fully supported by the existing VORTAC structure with the following modifications: Two new stations added, plus five existing low altitude stations converted to high altitude status. The costs are as follows:

Implementation (1982)	$ 597K
Maintenance-Annual	97K
Maintenance-1982-2000	1,843K
1976 Present Value Total	841K

RNAV Implementation Costs

The costs required (in-house and contractual) of the FAA to support the implementation of RNAV have been estimated by ARD-333 [44]. These cost values are listed in Table 4.25. They include the various R&D, training, route structure development and implementation and coordination costs required for successful implementation. While these estimates are tentative in nature due to the many variables which may impact on the actual costs of implementation, they provide a sufficiently reasonable estimate for the purpose of this report. As such, this estimated implementation cost ($19,825K) has been used in computing the FAA cost-benefit ratio. However, several points should be emphasized:

1) Approximately fifty per cent of the total estimated costs of implementation have been assumed for implementation planning and en route and terminal area route design development. These costs ($10,460K), extended over six years, assume both rather extensive use of contractor support for fast-time simulation and analysis efforts primarily ($3,260K) and 240 man years of in-house effort by the FAA ($7,200K), estimated broadly at $30,000 per man year. While these estimates appear reasonable for a systematic approach to the development and implementation of RNAV routes, other approaches to the implementation of RNAV routes might be taken by the FAA that could reduce these costs, but could possibly also result in a less systematic and delayed implementation.

2) A rather large training program has been assumed. These estimated training costs ($2,100K) extended over the first few years of the program assume that specialized RNAV training will be required initially. After the initial period, it is then assumed that specialized RNAV training course requrements will be reduced and eventually totally absorbed as a part of standard training programs at no additional cost. The total training cost estimate is dependent upon the approach taken by the FAA and may be reduced depending upon the degree of on-the-job training that can be provided as a part of existing facility training programs.

3) It has been assumed for the purpose of estimating implementation costs that some additional ATC resectorization requirements will be created by the integration of new RNAV routes into the ATC system; that new charting requirements will be added; and that flight check costs will be increased as new RNAV routes are implemented. Since resectorization occurs as a result of other factors not related to RNAV implementation, it can be assumed that some of the resectorization which might be required by RNAV as routes are introduced can be accomodated at the same time that selected sectors are being modified for other non-related reasons. Thereby the cost of RNAV related resectorization can be reduced to some extent. It has further been assumed that some, if not all existing high altitude routes would be phased out as new RNAV routes (both high and low altitude routes) are introduced. At

the same time VOR routes would also gradually be phased out as RNAV routes are increasingly added to the system. The schedule by which new RNAV routes are introduced and the number and schedule for existing routes to be deleted is unknown at this time. Therefore, flight check costs and charting costs are difficult if not impossible to estimate with any degree of accuracy today. Not withstanding this problem it has been necessary to establish some broad estimate of what these costs might be. It has therefore been estimated that the combined cost of ATC sector reconfiguration, flight checks and charting costs directly attributable to RNAV implementation would total $7,265K extended over six years. (i.e., 1979 - 1984).

4) While it is acknowledged that all of the preceding cost estimates are based on judgement and assumptions, the total implementation cost ($19,825K) allows for adjustments within the individual cost components.

5) In any event, while substantial increases in the actual cost of implementation over those estimated might occur, which would affect the benefit/cost ratio of 9.9 (see Section 4.4 below), actual implementation costs would have to rise to $33,600K (or 1.7 times that estimated) to reduce this cost benefit ratio to 6.0.

Table 4.25 RNAV Implementation Costs

Year	Cost
1977	$ 850K
1978	1840K
1979	3520K
1980	4130K
1981	3130K
1982	2950K
1983	1225K
1984	1050K
1985	700K
1986	430K
TOTAL	$19,825K
1976 P.V.	$12,949K

4.3 AIR CARRIER PASSENGER BENEFITS

In Section 4.1, the aircraft time savings which are expected to result from each attribute of RNAV (terminal benefits, enroute route length, VNAV descents and 4D at M&S sites) are documented. However, these time savings are also experienced by the aircraft passengers and are of benefit to them. Recent studies which compute passenger time benefits due to various ATC improvements (such as Reference 51) utilize passenger time values which range from $10 to $15 per hour, and more. In this report, a value of $12 per hour shall be used. The resulting passenger time benefits are expressed in Table 4.26, which lists aircraft hours saved, average passengers per aircraft,

and dollar value of savings. The average passenger load data was taken from 1975 CAB data [45]. The overall savings from years 1982 through 2000 are 588 million passenger-hours (67,000 passenger-years), worth over $7 billion to the passengers affected.

Table 4.26 Air Carrier Passenger Benefits, 1982-2000

AIRCRAFT HOURS SAVED:	4EWB	3EWB	4ESB	3ESB	2ESB	TOTAL
60 Terminal Hubs	204K	440K	23K	683K	494K	1844K
Route Structure	197K	705K	75K	767K	200K	1945K
VNAV Decents	8K	91K	15K	262K	216K	592K
4D at 24 M&S Sites	261K	576K	33K	889K	596K	2355K
TOTAL AIRCRAFT HOURS	670K	1812K	146K	2601K	1506K	6736K
Average Passengers/AC	180.4	117.6	77.4	64.4	50.3	— —
Passenger Hours	120.9M	213.1M	11.3M	167.5M	75.8M	588.5M
Value @ $12/Pass-Hr	$ 1450M	$2557M	$136M	$2010M	$909M	$7062M
Present Value Passenger Benefit	$ 310M	$ 532M	$ 41M	$ 468M	$221M	$1572M

4.4 PRESENT VALUE BENEFIT/COST ANALYSIS

The objective of this section is to quantify the attractiveness of RNAV implementation from the standpoint of financial planning. This requires the expression of costs and benefits in terms of their discounted present values and then in terms of their present value benefit/cost ratio. If this ratio equals 1.0, the cost expenditure is technically justified. B/C (Benefit/Cost) ratios significantly exceeding 1.0 imply a very efficient utilization of investment funds. Discounting procedures specified by OMB (Reference 43) are used in the following including the use of a 10% discount rate.

Air Carrier Benefit/Cost Ratio

Since both air crarrier benefits and costs have been well defined, it is possible to compute the benefit/cost ratios for air carriers independently of other factors. Two ratios are presented which represent the low fuel/aircraft time cost assumption and the high cost assumption separately. The results are stated in Table 4.27, which shows overall benefit/cost ratios of 2.9 and 5.0 for these two assumptions. The two assumptions should cover the range of costs to be encountered, although the higher cost assumption should more nearly account for

Table 4.27 Air Carrier Present Value Benefits and Costs, 1982-2000

	4EWB	3EWB	4ESB	3ESB	2ESB	TOTAL
PV Costs	$49.1M	$210.5M	$12.3M	$123.9M	$46.3M	$442.2M
PV Benefits:						
Low Cost Assumption	$232M	$432M	$ 40M	$397M	$200M	$1302M
High Cost Assumption	414M	775M	62M	630M	311M	2193M
1976 B/C Ratio:						
Low Cost Assumption	4.7	2.1	3.3	3.2	4.3	2.9
High Cost Assumption	8.4	3.7	5.0	5.1	6.7	5.0

actual costs and most airline accounting practices. Such high B/C ratios suggest that the implementation of RNAV is an extremely wise step from the airline point of view. It should be understood, however, that the individual economics of each installation would be even better than shown by these figures. This is a result of the fact that the present analysis considers a fixed time period where RNAV equipment is continually purchased as aircraft are added to the fleet, even though those equipped later do not have the opportunity within the fixed time period to earn a return on investment for as many years. This effect shows up strongly in the case of the 3EWB aircraft where the B/C ratios are somewhat lower than for the other aircraft types, since the rate of growth of the 3EWB fleet is projected to become, and remain, very high throughout the period to year 2000 (see Table 4.2 for fleet projections).

ATC System Benefit/Cost Ratio

ATC system benefits and costs have also been well defined, and so the RNAV ATC B/C ratio may be computed, as in Table 4.28. The result, 9.9, is extremely large, and in view of the benefits to the airlines exhibited above, highlights the overall attractiveness of RNAV.

Table 4.28 ATC Present Value Benefits & Costs, 1982-2000

Present Value Benefits	$136.7M
Present Value Costs	13.8M
1976 Benefit/Cost Ratio	9.9

Overall RNAV Benefit/Cost Assessment

The present value costs and benefits shown so far, plus the others developed in this study are summarized in Table 4.29. The other factors included are the present value airline passenger benefits and present value general aviation user costs. GA user benefits have not been projected through year 2000 in this study since the forecast data necessary were not available; this results in a conservative estimate of the overall B/C ratio. The resulting overall ratios are 5.5 and 7.1, which of course are quite large. Besides GA benefits, other factors which tend to make this figure conservative include the following: First, the air carrier equipage costs used were high, since (a) highly sophisticated systems were presumed for the wide body aircraft, although they are not necessary to derive the benefits, and since (b) dual RNAV installations were presumed in all air carrier aircraft. Also of great significance is the fact that recent simulations [37] have shown that RNAV can improve terminal arrival capacity, reducing delays significantly in the process; these savings have not been included in this analysis. To illustrate the magnitudes of these impacts, the substitution of single RNAV systems for the dual airline installations would boost overall B/C ratios from 5.5 to approximately 8.5, and 7.1 to approximately 11.0.

Table 4.29 Overall RNAV Benefit/Cost Ratios

	Low Cost Assumption	High Cost Assumption
PV Air Carrier Benefits	$1302M	$2193M
PV ATC System Benefits	137M	137M
PV Passenger Benefits	1572M	1572M
TOTAL PV Benefits	$3011M	$3902M
PV Air Carrier Costs	$ 442M	$ 442M
PV GA Costs	95M	95M
PV ATC System Costs	14M	14M
TOTAL PV Costs	$ 551M	$ 551M
Benefit/Cost Ratio	5.5	7.1

A final point of significant interest regards fuel savings. The costs of fuel saved are included in the above figures. However, since fuel is a limited resource, the total magnitude of the fuel savings to the year 2000 is of interest also. This savings was found to be 10,371 million gallons. This amount significantly exceeds the total domestic air carrier fuel consumption for 1975, which was 7279 million gallons [45]. Should energy conservation efforts be carried to the point where growth in airline services is curtailed, the overall RNAV benefit in terms of time and fuel savings may be somewhat reduced. By the same token, such a situation could result in extremely high fuel prices, inflating the fuel savings dollar benefit.

5.0 CONCLUSIONS

The conclusions of this study of RNAV/UG3RD interactions are presented below. They are organized according to the UG3RD program area affected.

5.1 DISCRETE ADDRESS BEACON SYSTEM

- The adoption of a comprehensive RNAV route structure, and the trend to preplanned direct flight plans, will not affect the plans for DABS site locations or implementation schedules.

- The DABS data link feature can be used to transmit clearances and control messages in RNAV-compatible terms with no modifications to the DABS system itself, and with only minor changes to the NAS/ARTS computer software. Different (although not significantly more costly) airborne DABS control message displays would be required for RNAV users in comparison to the basic radar vector control display. Data link channel usage will diminish slightly as RNAV usage becomes widespread.

- The DABS data link feature could potentially be used for providing, on demand, waypoint data to RNAV aircraft desiring such service (Route Data Delivery concept), in order that cockpit procedures might be simplified. This would not increase data link usage to any significant extent, although there could be a finite increase to the NAS/ARTS computational workload as a result.

- The DABS surveillance and data link functions were not found to be necessary to the successful and beneficial implementation of RNAV as the primary navigation system.

5.2 INTERMITTENT POSITIVE CONTROL

- The trend to an RNAV environment is not seen to have any substantial impact on IPC usage, although any such impact would definitely take the form of a reduction to the IPC requirement.

- The IPC function should recognize the beneficial effects which the provision of RNAV, or RNAV-compatible, messages would bring to IPC and its potential for user acceptance, particularly in terms of the RNAV ability to maintain orientation and facilitate return to original course.

5.3 FLIGHT SERVICE STATION MODERNIZATION

- Flight service automation will have to be configured to process (including error and route discontinuity detection) RNAV routes as well as conventional flight plans, although this simply amounts to a moderate increase in data base size, not a complication to system logic since the flight plan formats are very similar.

- RNAV has virtually no effect on the preparation and delivery of mass or individual weather briefings, either pre-flight or in-flight.

- The usage of RNAV routes will have no effect upon the transfer of flight plan data from FSS to affected centers and TRACONs.

- The FSS concept could be expanded such that flight planning services could be provided automatically to RNAV users, although this would require significant changes and some added FSS capabilities.

5.4 UPGRADED ATC AUTOMATION

- Based upon the M&S techniques analyzed in this study, RNAV procedures may be integrated within a Metering and Spacing environment without creating any significant procedural or software problems. RNAV and conventional (radar vector) traffic may be mixed freely in an M&S environment.

- Arrival time control capability of M&S (8 seconds, 1σ) is not affected, either positively or negatively, by the presence of RNAV.

- Aircraft time controllability (range of delay available expressed on a statistical basis) of M&S is actually improved 6% through the use of RNAV procedures.

- The usage of RNAV with M&S results in a net decrease in controller workload through the ability of RNAV to alleviate the rigorous discipline of a radar vector M&S environment.

- The integration of 4D RNAV procedures within an M&S environment will improve all performance measures: arrival time control (5 sec, 1σ), time controllability (20% improvement), and controller workload (reduced message count).

- The requirement of the Control Message Automation feature to process RNAV as well as conventional control messages will affect the logical design of parts of CMA, but will not significantly impact overall computer storage or execution time resource requirements.

- The Central Flow Control system, as presently planned, is not oriented towards specific routes of flight, and so any RNAV impact would be minimal.

- RNAV may be able to provide increased utilization of existing Center airspace for holding arrival aircraft; this and other UG3RD improvements may reduce the dimension of the CFC problem.

5.5 MICROWAVE LANDING SYSTEM

- RNAV delivery errors at the RNAV/MLS coverage interface are not of sufficient magnitude to cause significant transition problems.

- At most airports where wide-beam MLS coverage would be installed to support noise abatement procedures, RNAV capabilities may be used instead, which may reduce wide-beam MLS implementation requirements.

- In all but very exceptional cases, a true "curved profile" is not necessary for successful implementation of noise abatement approach procedures. Straight line-segment profiles, presuming ordinary maneuver anticipation techniques, may be substituted.

- RNAV IFR noise abatement procedures which intercept existing ILS paths may be instituted immediately at many airports.

- MLS elevation data, being of a geometric rather than barometric nature, induces vertical guidance incompatibilities which increase with altitude. This problem is eliminated if barometric data is used above 4000 feet AGL, while approaching aircraft transition to MLS elevation data below that altitude.

- Much of the route data storage, computational and display requirements of RNAV and MLS are in common. It would be of significant benefit to aircraft operators, and therefore to the RNAV and MLS programs themselves, if combined RNAV/MLS hardware were to be utilized. The cost of a combined system would not be much higher than the cost of an MLS system alone.

5.6 AIRPORT SURFACE TRAFFIC CONTROL

- The ASTC program is not expected to be affected by RNAV in any way.

5.7 WAKE VORTEX AVOIDANCE SYSTEM

- The WVAS program is not affected directly by RNAV, although RNAV control procedures may be beneficially used when unanticipated changes in the vortex conditions at any airport are detected.

5.8 GENERAL CONCLUSIONS

- No UG3RD program elements were found to either be required for or to significantly interfere with the successful and beneficial implementation of RNAV as the primary navigation system.

- An Extended Capability RNAV concept developed in this study, which requires no new or improved navigation aid development or implementation, could be applied to significantly improve the utility of RNAV Instrument Approach Procedures by allowing reduced MDA's and lower visibility minima.

5.9 BENEFIT/COST ANALYSIS CONCLUSIONS

RNAV benefits and costs were projected to the year 2000, as explained in Section 4. These dollar values were discounted to 1976 present values for total costs and benefits. The overall results are as follows:

- Present value air carrier equipage, etc. costs were estimated at approximately $442 million. Benefits due to airline operating cost savings were estimated to be somewhere in the neighborhood from $1.30 billion to $2.19 billion, depending on the interpretation of the cost factors comprising aircraft direct operating cost to be included in computing benefits. Therefore the projected 1976 present value air carrier benefit/cost ratio will range from 2.9 to 5.0, depending upon the same factors.

- The benefit/cost ratios discribed above represent the entire airline industry (domestic) as a whole, but are not appropriate as indicators of benefit/cost ratio pertaining to aircraft owned by individual airlines. For those cases benefits and costs should be measured over an aircraft's lifetime. In the present case, they were computed to the year 2000, and all equipage costs for aircraft purchased through that year are included on the costs side of the equation. Thus, benefit/cost ratios presented here understate the case on an individual basis.

- RNAV savings in terms of reduced time enroute and reduced terminal delays will also be experienced by airline passengers. The overall present value benefit of airline passenger time savings, computed at a value of $12 per passenger-hour, is $1.57 billion.

- With respect to the ATC system, RNAV impacts costs and savings in several ways. Significant cost factors include the RNAV implementation process itself (present value cost $13 million) and enroute VORTAC improvements ($1 million). Benefits due to cost savings include terminal VORTAC savings (present value savings $8 million), terminal controller productivity savings ($8 million), and enroute controller productivity savings ($121 million), resulting in an overall benefit/cost ratio of 9.9.

- Overall 1976 present value RNAV costs, including those to ATC, the airlines and general aviation, over the period to 2000 are $551 million. Overall domestic RNAV benefits, to air carriers, their passengers and the ATC system range from $3.01 to $3.90 billion resulting in an overall benefit/cost ratio ranging from 5.5 to 7.1.

- The present value benefit cost ratios found in this study, which range from 2.9 to 9.9, are extremely high. Many projects and programs are considered justified where the ratio only slightly exceeds 1.0, or even where it is less than 1.0 and other (non-quantifiable) benefits are expected to result. Many non-quantified benefits also are expected from RNAV, including safety enhancements and improved efficiency of operation. All of these factors speak very favorably towards early RNAV implementation.

REFERENCES

1. "Baseline and Implementation Scenario", UG3RD Analysis Work, FAA, AVP-100, October 7, 1975.

2. "Area Navigation Route Width Requirements", A.R. Stephenson, W.H. Clark, Systems Control, Inc., FAA-RD-77-21, December 1976.

3. "DABS: A System Description", P.R. Drouilhet, MIT Lincoln Laboratory, FAA-RD-74-189, 18 November 1974.

4. DABS Briefing given by Richard Haskin, FAA, ARD-210, 7 November 1975.

5. "An Advanced Air Traffic Management Concept Based on Extensions of the Upgraded Third Generation ATC System: Summary Report", R.M. Harris, et al, MITRE Corporation, FAA-EM-73-10A, March 1974.

6. "Area Navigation High Altitude Payoff Analysis; Enroute Fast Time Simulation Results", Ricardo Cassell, FAA, Systems Research and Development Service, FAA-RD-76-26, December 1975.

7. "ATC Performance Requirements for Developing Prototype Versions of the Discrete Address Beacon System", A. Haines, et al, MITRE Corporation, FAA-EM-73-6, April 1973.

8. "Implementation of Area Navigation in the National Airspace System: An Assessment of RNAV Task Force Concepts and Payoffs", W.H. Clark, et al, Systems Control,Inc., Champlain Technology Industries, FAA-RD-76-196, August 1975 .

9. "Terminal Area Design; Analysis and Validation of RNAV Task Force Concepts", E.D. McConkey, Systems Control, Inc., Champlain Technology Industries, FAA-RD-76-194, October 1975.

10. "Approval of Area Navigation Systems for Use in the U.S. National Airspace System", AC 90-45A, Department of Transportation, Federal Aviation Administration, February 1975.

11. "Three and Four Dimensional Area Navigation Study", N.B. Hemesath, et al, Rockwell International, Collins Radio Group, FAA-RD-74-150, June 1974.

12. "Provisional Signal Formats for the Discrete Address Beacon System (Revision 1)", P.R. Drouilhet, MIT Lincoln Laboratory, FAA-RD-74-62, 25 April 1974.

13. DOT Air Traffic Control Advisory Committee, Final Report, December 1969.

14. "AATMS General Specification, Volume 2, Appendix C - Demand Analysis", D. Goldman, et al, MITRE Corporation, May 1973.

15. "Economic Impact of Area Navigation", Eric H. Bolz, et al, Champlain Technology Industries, Systems Control, Inc. (Vt),FAA-RD-75-20, July 1974.

16. "A Proposal for the Future of Flight Service Stations", OST/FAA Flight Service Station Evaluation Team, Aug. 1973.

17. "System Description: Automated Flight Service Station System", Federal Aviation Administration/Systems Research and Development Service, Coordination Draft, March 19, 1975.

18. "Flight Services", (Handbook 7110.00), DOT/Air Traffic Service, April 1, 1969.

19. Buck, Henry J., Chief, FAA/SRDS, FSS Branch/Systems Design Section (ARD 442), Washington, D.C., (personal discussion).

20. Templeton, Billy D., WMSC Facilities Chief, National Communication Center/Weather Message Switching Center (NARCOM/WMSC), Kansas City, Missouri, (personal discussion).

21. Brothers, Elmer, FSS Facilities Chief, Atlanta FSS, Charlie Brown County Airport, Atlanta, Georgia, (personal discussion).

22. "Impact of Area Navigation on ATC Automation", FAA/SRDS/ARD-100, draft report, October, 1975.

23. "Area Navigation Waypoint Designation Standards", Adams, R.J., Systems Control, Inc. (Vt), FAA-RD-75-122, August 1975.

24. "Master Plan for the Flight Service Station Modernization Program", FAA, SRDS, report FAA-FSS-01, June 1976 (Review Draft).

25. "Central Flow Control Facility", FAA Order 7230.12A, 21 December 1970.

26. "Flow Control Procedures", FAA Order 7210.7B, 18 January 1974.

27. "Airport Information Retrieval System (AIRS) System Design", Manuel F. Medeiros, Julie Sussman, DOT, Transportation Systems Center, FAA-RD-73-77, July 1973.

28. "Central Flow Control Computer Program Functional Specification", June 28, 1976, contained in RFP-LGR-6-7587, "Central Flow Control Programming Subsystem".

29. "Computer-Aided Metering and Spacing with ARTS III", Computer Systems Engineering, Inc. FAA-RD-70-82, December 1970.

30. "A Proposed Metering and Spacing System for Denver", R.G. Gados, et al, MITRE Corp., MTR-6865, March 1975.

31. "An Operational Evaluation of Flight Technical Error", R.J. Adams, Champlain Technology Industries Div, System Control Inc., FAA-RD-76-33, October 1976.

32. "Alternative Approaches for Reducing Delays in Terminal Areas", M.Meisner, et al, FAA-RD-67-70, November 1967.

33. "Three and Four Dimensional Area Navigation Study", N.B. Hemesath, et al, Collins Radio Group, Rockwell International, FAA-RD-74-150, June 1974.

34. "RNAV Impact on ATC Automation", Ronald Braff, F.O. Yezek, MITRE Corp., MTR-6612, 12 March 1974.

35. "Analysis of RNAV Utilization and Integration with M&S", Computer Systems Engineering, Inc., for FAA, SRDS, CSE-R-145, August 1972.

36. "Automated Metering and Spacing with Area Navigation", S.C.Mohleji, MITRE Corp.,for FAA, OSEM, MTR-6431, June 1973.

37. "Area Navigation/Vertical Area Navigation Terminal Simulation", W. Crimbring, J. Maurer, NAFEC, FAA-RD-76-28, April 1976.

38. "Application of Area Navigation in the National Airspace System", FAA/ Industry RNAV Task Force, February 1973.

39. "United States Standard for Terminal Instrument Procedures (TERPS)", FAA Handbook 8260.3A.

40. "Evaluation of Digital Data Broadcast for Area Navigation", K. Warner, M. Hughes, R. Elliott, Sierra Research Corp., Champlain Technology Industries, FAA-RD-76-60, April 1976.

41. "Agency Names Top Priorities", <u>FAA Headquarters Intercom</u>, DOT, Number 75-41, October 14, 1975.

42. "A New Guidance System for Approach and Landing", Report of Special Committee 117, Radio Technical Commission for Aeronautics, DO-148, December 1970.

43. "Discount Rates to be Used in Evaluating Time-Distributed Costs and Benefits", Circular A-94 Revised, Office of Management and Budget, March 27, 1972.

44. RNAV implementation plans and cost estimates provided by R. Cassell, FAA-ARD-333, November 1976.

45. "Aircraft Operating Cost and Performance Report", Volume X, July 1976, Civil Aeronautics Board.

46. Telephone Contacts with John Kaufman, Delco Electronics; Jerry Gaspar, Collins Radio Group; and Capt. Roy Berube, National Airlines, October 1976.

47. "FAA Air Traffic Activity, Calendar Year 1974", DOT, FAA, Office of Management Systems, March 1975.

48. "FAA Statistical Handbook of Aviation, Calendar Year 1973", DOT, FAA.

49. "Preliminary Analysis of Impact of RNAV on ATC Economics", E.H. Bolz, Champlain Technology Industries, Division of Systems Control, Inc. (Vt), for DOT, FAA, July 1973 (Draft).

50. "Estimation of UG3RD Productivity Impacts", DOT, FAA, Office of Aviation Policy, June 1976 (Draft).

51. "ARTS-III Enhancements Costs and Benefits", K. Willis, METIS Corp., FAA-AVP-75-3, September 1975.

52. "An Overview and Assessment of Plans and Programs for the Development of the Upgraded Third Generation Air Traffic Control System", FAA, OSEM & MITRE Corp., FAA-EM-75-5, March 1975.

APPENDIX A

RNAV INTERACTION WITH DABS/IPC

A.1 DABS SURVEILLANCE SYSTEM IMPACTS

INTRODUCTION

The Discrete Address Beacon System is intended to eventually replace the existing ATC Radar Beacon System as the primary air traffic surveillance tool in the U.S. The DABS plan includes several improvements to the basic secondary radar capability besides the major improvement, discrete addressing. In particular, improvements in antenna design, the use of monopulse techniques for bearing resolution and improved ranging techniques will result in much more accurate tracking data. The use of discrete addressing and improved data coding techniques will greatly enhance track reliability and integrity by eliminating much of the noise in the present radar environment and improving signal noise immunity. The DABS radar network is planned to achieve widespread implementation by 1982 [1] and will be completely implemented by 1988. Area navigation is also expected to achieve widespread implementation in the same time period, and so it is of importance to examine RNAV procedures and requirements in order to determine if there are any ways in which RNAV would affect the surveillance performance required of the DABS network.

DABS performance measures which could potentially be impacted by Area Navigation include tracking accuracy, track update rate, tracking reliability, coverage area and redundancy of coverage, minimum coverage altitudes, antenna site locations and site implementation schedule. The degree to which these might be affected is highly dependent upon the particular ATC environment of concern and types of procedures used. In the analysis below the basic environments are discussed (enroute IFR, terminal IFR, and VFR/IFR mixed), followed by studies of special RNAV procedures (VNAV, 4D, and RNAV approaches to off-site runways).

ATC ENVIRONMENTS

Enroute IFR

The basic issues to be addressed in the enroute IFR environment (high and low altitude) are RNAV separation standards and route locations. The separation standards would potentially impact DABS surveillance accuracy, whereas the relocation of routes due to RNAV and Preplanned Direct (PPD) could affect coverage requirements or antenna site locations. While route widths in the enroute environment are anticipated to be slightly smaller in the future environment than at present (constant ±4 nm compared to ±4 nm with a 3.25° splay beyond 51 nm from the VORTAC [2]), the stated DABS accuracy specification [3] is so much narrower than the route width that such a minor improvement in route width requirement would be inconsequential from the point of view of surveillance for separation assurance. The stated accuracies are 0.1° in azimuth (0.17 nm at 100 nm) and 100 ft. in range, and current flight test results [4] indicate that actual performance could be even better than that.

The other issue concerning the enroute IFR environment is whether surveillance coverage requirements would be affected by the use of RNAV (and direct) routings. If so, the result could be that changes in DABS coverage requirement, antenna site locations or implementation schedule would be needed. If such a problem were to exist, it would only be of short duration, however, since plans call for redundant coverage of almost the entire CONUS down to 6000 feet AGL, and single coverage to much lower altitudes (2000-3000 feet AGL for the most part), by the mid to late 1980's [5]. In the high altitude environment, RNAV routes may deviate significantly from existing route locations. However, the origin and terminal points are approximately the same as for conventional routes, and so no problem would exist except in the areas between major city-pairs. These are also the areas where DABS would be implemented last, since the terminal hub areas are to receive DABS capability first. However, the high altitude environment is also the area with the least severe surveillance requirement, since longitudinal separations are large (due to the high speed aircraft) and since terrain is seldom a problem in affecting coverage. This environment is currently being served well by the ARTCC ATCRBS net, and will continue to be until replacement with DABS sites occurs. Also, the switch to RNAV operations actually has been shown to reduce the number of potential airspace conflicts encountered for a given level of enroute traffic. A recent simulation study [6], which evaluated operations on the existing high altitude route structure in comparison to RNAV route structures developed for purposes of those studies, found that airspace conflicts would be reduced by over 25% when all traffic operated along the RNAV routes rather than on the present structure. The transition of traffic to RNAV was found to present no problem either, since simulations using a mix of RNAV and VOR operations showed equivalent reductions in conflicts experienced. In view of the above, the high altitude enroute environment is not expected to exhibit any RNAV-related problems which would affect DABS site implementation.

Low altitude RNAV routes will also be displaced from existing VOR routes, which travel from VORTAC to VORTAC. However, these displacements will not be very large for the following reasons. First, routes cannot be displaced very far since the nominal coverage region of a low altitude VORTAC extends only 40 miles; thus the route could not be moved more than 20-25 miles and yet maintain an appreciable amount of coverage along its length. Furthermore, low altitude routes usually "meander" slightly as they run from GA airport to airport, with each segment being fairly short. Since they are short, significant deviations from direct routings would not be expected to be found. Certain low altitude operators may fly preplanned direct over longer distances, although this practice is not expected to be very common. Finally, many operators will not be RNAV equipped, and many VOR routes will be retained, so a significant percentage of low altitude traffic will use existing routes. As a result, low altitude RNAV routings should not impact DABS site implementation plans to any significant extent.

Terminal IFR

RNAV operations in terminal areas may have an impact on DABS surveillance requirements for three reasons: accuracy requirements, the use of self-navigated SID/STAR procedures, and the use of RNAV for conducting instrument approaches. The present terminal area route width requirement of ±2 nm is expected to be retained as RNAV is fully implemented [2], which will primarily affect the hub terminals since their operations will be almost totally RNAV. As discussed under the enroute section, the DABS accuracy is far better than the 2 mile requirement and, for that matter, is quite a bit better than existing ATCRBS performance. Therefore, RNAV implementation should not affect DABS accuracy requirements.

A potential exception to the accuracy requirement issue concerns monitoring approach procedures conducted under RNAV guidance. First of all it should be noted that the use of RNAV for approaches at hub airports would be the exception rather than the rule (except possibly for providing the vertical guidance signal for two-segment approaches). The reason for this is simply that nearly all commonly used major runways are, or will be, instrumented with ILS and/or MLS, which would be used in preference to RNAV guidance. This is particularly true of closely-spaced parallel runways, where the use of RNAV would not be appropriate. RNAV would be used under the following conditions: as a backup to failed airborne ILS equipment (an exceptional situation), or as a means of approaching a non-ILS runway. In the latter case, which is the only one of significance, RNAV would be selected in preference to other existing procedures (VOR,NDB) by RNAV-equipped aircraft, since in many cases slightly lower minimums would result and a circling approach could often be avoided. In nearly all cases the RNAV approach would be conducted at least as accurately, probably more accurately, than the alternative procedures, and so would be preferable from all points of view. Also, since DABS azimuth accuracy improves when approaching the antenna (which would probably be on the airfield), such that azimuth errors are less than one hundred feet within ten miles range, monitoring of such procedures should present no problem.

Regarding the subject of self-navigated SID and STAR procedures, which would replace most radar vector requirements, the only remaining issues other than accuracy are update rate and track reliability requirements. Present ATCRBS update rate for terminal radars is four seconds, which is expected to be continued when DABS is implemented [7]. Since the RNAV routes are to be self-navigated rather than being controlled through ground surveillance, the requirement for timely surveillance information is actually reduced rather than increased. Therefore, there would be no reason to require a higher update rate because of the use of RNAV arrival/departure procedures. A similar argument applies to the issue of track reliability. Temporary or prolonged loss of data is not immediately problematical for RNAV users since they will continue to navigate the desired path, while radar vectored aircraft are considerably more difficult to deal with under such conditions.

Mixed VFR/IFR Traffic

Mixed VFR/IFR traffic occurs primarily in the terminal area and low altitude enroute environments. The primary functions of concern here are separation of IFR traffic from VFR, which is done manually now, controller workload permitting, but will be done as a required function when IPC is implemented. In accomplishing this function it makes little difference what type of route are being navigated by the IFR aircraft, VOR or RNAV. Also, the factors described in earlier discussions pertaining to accuracy, update rate, etc., apply also to the mixed environment case. The only aspect of coverage which might be affected is the minimum altitude covered. However, low altitude coverage of DABS is supposed to be at least as good as ATCRBS, and so as DABS is implemented, coverage should improve. As stated before, eventual full DABS implementation will result in coverage down to 2000-3000 feet AGL throughout nearly all of CONUS, and so should include virtually all IFR operations.

SPECIAL RNAV PROCEDURES

VNAV Arrival/Departure Procedures

VNAV procedures, which may be optionally used by aircraft operators in order to gain operational and fuel saving benefits [8], do not affect surveillance requirements since altitude determination is not a surveillance function. Altitude data is determined from the encoded transponder return. If VNAV were to be used as the primary method of providing altitude separation, and particularly if, through the improvement of VNAV system accuracies, closer separation standards were used rather than those presently in force [9,10], some form of ground-derived altitude data may be required in order to obtain accurate surveillance of the vertical profiles. This would probably be accomplished through the use of monopulse radar techniques. However, since there are no formal plans at present to require VNAV terminal operations or significantly reduce VNAV separation standards, the institution of vertical tracking capability should not be necessary.

Time Control (4D) Navigation Procedures

The use of Area Navigation equipment which is capable of providing time-of-arrival guidance (4D RNAV) should eventually serve as a very useful adjunct to Metering and Spacing automation, since it will relieve the ground-based system of some time control chores and provide more accurate control of arrival time [11]. Through more accurate arrival time control, interarrival spacing along the final approach course may be reduced slightly, which can yield significant benefits in terms of delay reductions [8]. 4D operations could potentially impact DABS surveillance system position and velocity tracking accuracy requirements, since arrival time control accuracies on the order of five seconds are desired. A five second time control error is equivalent to a 1300 ft position error (at 160 kt), and so tracking accuracy would have to be considerably better than that. As stated earlier, the DABS accuracy specification is 0.1° and 100 ft, which should be sufficient for the most stringent time control monitoring requirements.

Off-Site Located RNAV Approach Procedures

This section concerns the possible requirement for DABS monitoring of RNAV approaches to runways which are out of the coverage region during the final phases of the approach. The loss of coverage may be due simply to the range between the DABS site and the airport in question, or to intervening terrain features. Radar coverage is not at present required for the execution of RNAV approach procedures, nor is it required for other types of instrument approach procedures. The RNAV capability greatly expands the flexibility available for designating approach procedures: straight-in approaches may often be substituted for existing circling approaches, and in some cases approaches may be designated for runways for which no approach procedure currently exists. However, due to its very nature, RNAV is somewhat more prone to the incidence of procedural errors than are some other instrument approach techniques. Since procedural errors during approach can be very dangerous, it might be desirable to require that DABS coverage down to approach minimums be available in order for an RNAV approach to be designated. Conversely, it could be required that approach minimums be

set at the lower limit of existing DABS coverage. A major argument against such requirements is that the ATC system is not responsible for the proper execution of an otherwise safe approach procedure. Even so, the ATC system might, at some future time, deem it to be a proper function to provide surveillance services as an added safety function. If that should be the case, it would not be necessary to provide coverage down to approach minimums, however, in order to assure proper execution of the procedure. Most RNAV approach procedures are designed using a final approach path length of approximately ten miles. This means that the intermediate approach fix may be placed as much as 2500 feet higher than approach minimums, which should be within DABS coverage in most situations. As a result, the earlier part of execution of the final approach segment could be monitored, which should provide sufficient protection against procedural error since in most cases most or all navigation data will have been inserted in the RNAV computer by the flight crew by that time. It is highly recommended that, for purposes of procedural error avoidance, the final approach fix be defined as DME range from the missed approach point, rather than as a separate waypoint. In those cases where no surveillance service can be provided at all, the face of the approach plate itself could be so annotated in order to make certain that the flight crew is aware of that fact.

A.2 CANDIDATE DABS DATA LINK MESSAGE FORMATS

INTRODUCTION

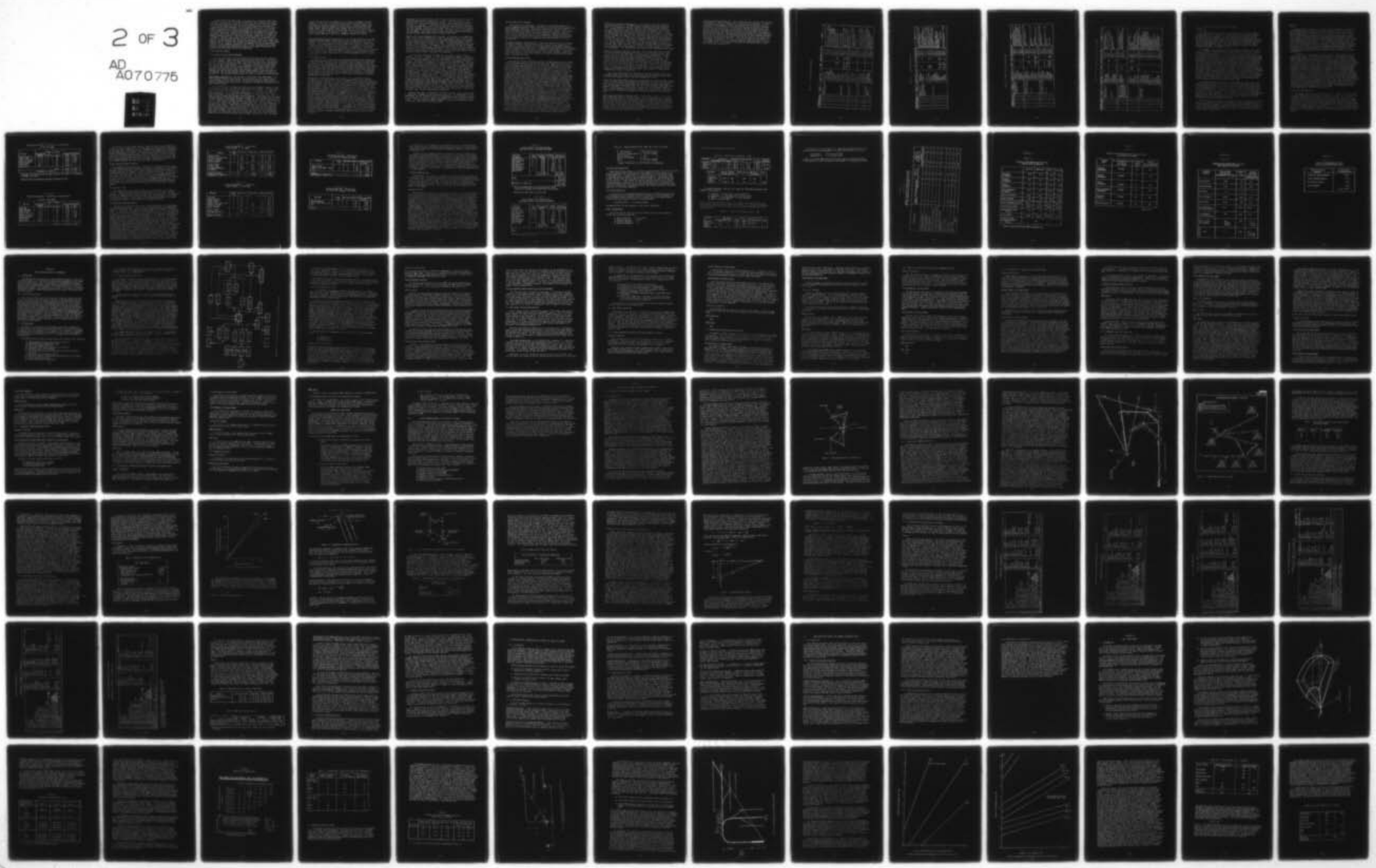
The purpose of this study is to determine the possible types of DABS messages which would be appropriate for IPC usage, for ordinary ATC control and for control of RNAV aircraft, and to identify the required message information content, and to design an appropriate data format to accomplish the purposes of each message using a minimum number of DABS link data frames. The results of this analysis are to be used as inputs for several other parts of the UG3RD Impact Study. Specifically, they will be used for the study of DABS data link usage and saturation, for the study of airborne RNAV interface and display considerations, and for the study of Control Message Automation effects. It should be understood that it is not the intent of the present study to specify the message formats in their final form to be used when DABS is implemented but rather to design a candidate set of message formats (particularly for RNAV control messages) representative of those which will actually be implemented for purposes of the other analyses to be conducted under the RNAV UG3RD Impact Study. The types of messages considered for this study include radar vector instructions (for IPC and general control usage), proximity warning messages (IPC), ATC clearance messages, RNAV Tactical Control Messages (equivalent to the radar vector), and MLS approach monitor messages. In addition, several messages which would serve RNAV users which may optionally be implemented as a DABS service were identified and studied. These concern the distribution of waypoint data. The specific message types studied include a filed route data request message, a route data delivery (RDD) message, a direct route clearance request, and a direct route data request message. These data services may or may not be implemented as a part of the DABS structure, depending upon demand and the degree of difficulty associated with their implementation.

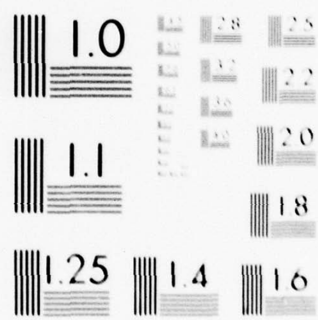
MESSAGE FORMAT DESIGN CONSIDERATIONS

The first step in the development of a data format appropriate to a particular type message is to decide which data items are necessary in order to fulfill the intended purpose of the message, and which items are only ancillary to the purpose of the message and therefore may be dropped from the message if no room is available. A major constraint upon the way data is arranged and coded digitally is the limitation in computer logic capabilities which would be available in airborne displays and interfaces to decode the data. The effect of this is that data items must be coded in the manner for which the data is to be used or presented; e.g., numeric data must be BCD format, alphanumeric data in a character code (six-bit BCD or ASCII), and binary data in a natural binary format. Also, data packing techniques cannot be used. The airborne units cannot be assumed to have unpacking or code conversation capabilities. The DABS data link format [3] for both uplink (G/A) and downlink (A/G) messages allows a message text length of 56 bits. However, the DABS format contains no provision for display or airborne device addressing or pilot acknowledgement requesting. For uplink messages three bits are required for device addressing and one for acknowledgement request; for downlink messages four are required for originating device address [12]. Additional bits may be required for display device control, message type indication and message frame numbering. Each DABS message frame allows 56 bits of data, although multiple frames may be used for long messages; in such cases all housekeeping required to identify or number frames must be contained in the 56 bit field. Obviously, the use of as few frames as possible for each message type is highly desirable in that DABS channel usage is reduced and airborne display system complexity is reduced. All of these considerations reduce the field available for actual data transmission well below 56 bits.

AD-A070 775 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
SYSTEMS INTEGRATION: RNAV AND THE UPGRADED THIRD GENERATION SYS--ETC(U)
DEC 76 E H BOLZ, R W SCOTT, A R STEPHENSEN DOT-FA72WA-3098
UNCLASSIFIED FAA-RD-77-22 NL

2 OF 3
AD
A070775





MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

In designing the message formats presented herein, compromises were often necessary. In particular, information requirements were reviewed, data resolution and range required to serve the specific purposes were carefully evaluated in light of the operational uses for which the messages were intended, and coding shortcuts were evaluated, such as dropping leading zero bits when appropriate or presuming the existence of permanent bit settings in display units. A prime example of this is the presumption that for all communication frequencies (which range from 118.000 to 135.975 MHZ) that 100 MHZ may be assumed to be supplied by the display, and therefore need not be transmitted. An example of dropping leading zero bits is the coding of heading command (which ranges from 1 to 360°). The first digit ranges from zero to three, and so requires only two bits for coding rather than the four bits required to code zero through nine. Actually, one bit could also be dropped from the second digit since it only ranges from zero to six. However, the dropping of embedded bits was avoided wherever possible. In the detailed explanations which follow, individual coding conventions are discussed where appropriate except in cases where leading zeros are dropped, since that short cut was used extensively.

DETAILED MESSAGE FORMATS

Intermittent Positive Control Messages

Two distinct message types are required for IPC usage; the basic positive collision avoidance command, and the proximity warning indication. The collision avoidance command is merely an automatically generated radar vector instruction, and so it has been combined with other radar vector features into a more general ATC control radar vector message. It is important to note that the most basic IPC displays may respond only to certain portions of the message format, which are those activated when the radar vector message is indicated to be an IPC command; more complex radar vector displays would respond to the other parts of the command. All of these message formats are presented in detail in Tables A.1 through A.4. The proximity warning indication (PWI) is unique to the IPC function.

Radar Vector (Function #1): This message is configured in two DABS frames. The first contains the most essential data, and would activate the simplest radar vector displays, and the IPC displays. The second frame may be transmitted and contains additional data which could be decoded and displayed by more sophisticated radar vector displays.

The first four bits of frame one contain the acknowledgement request bit (which lights the pilot response push buttons) and three device address bits, which would be set to the IPC/radar vector device address. Bit five contains the frame number, zero in this case. Bit six indicates whether this is an ordinary radar vector or an IPC command. In the case of an IPC command, only data items four, five, six, seven, twelve, thirteen and fourteen could be supplied. Item number four (bit seven) indicates whether the displays indicated by items five, six and seven (one bit each) are to be updated or the display cleared. If they are to be updated, the values are found in fields twelve, thirteen and fourteen respectively. That is to say, if item four were set to zero, and items five and seven were set to one, new heading and altitude values found in items twelve and fourteen would be displayed, replacing any pre-existing values. If bits four, five, six and seven were set to one, all three displays would be cleared and turned off. In the case of an ordinary ATC radar vector command, (item three set to zero), the other fields may be used when applicable. If items eight, nine, ten or eleven are used, then the second DABS frame will also be transmitted upon the next DABS interrogation, since that frame

contains the data fields for communications frequency assignment, altimeter barometric setting and secondary speed and altitude values which are used when ranges of altitude and speed are permissible. Only more complex radar vector displays would be capable of decoding and displaying data from the second frame. Simple displays could, however, utilize fields fifteen and sixteen of the first frame which indicate when the stated altitude is modified by an "at-or-below" or "at-or-above" clearance. Data coding shortcuts used in the second frame are listed in the "Comments" column of the table.

Proximity Warning Indicator (Function #2): This message requires but one DABS frame and is quite simple. The display consists of thirty-six lights (see Reference 3 for a description of display) which are either off, illuminated or flashing. This message will cause one or more of the thirty-six lights to be flashed, turned on continuously or turned off. For example, if item two were set to zero, item three were set to one and the fifteenth bit in field four were set to one, the fifteenth lamp would be set to the flashing state, regardless of its previous state. Direct IPC control commands are also included in this message, requiring nine additional bits. These are redundant with the radar vector IPC message.

ATC Clearance Message

In addition to the radar vector message discussed above, three other types of dedicated airborne displays have been identified which would be appropriate to delivery of ATC control messages. Naturally, these displays could be combined into several arrangements or combined with other equipments, such as the RNAV computer. Other more complex display or communications devices, which would use the extended length message (ELM) format available through DABS, have not been included in this analysis since they are intended mainly for secondary ATC control purposes and, possibly, private communications purposes. In addition, such messages are typically not time-critical, and so do not impact peak DABS channel usage significantly.

Precoded ATC Clearance Messages (Function #3): The precoded ATC clearance message display is intended for efficiently communicating routine, repetitive clearance messages such as taxi clearance, takeoff clearance, holding instructions, route assignments (SID/STAR), clearance limit instructions, expect further clearance instructions, etc. The message format proposed herein presumes that the display system is capable of displaying several standard messages (up to sixteen are provided for airborne and for ground ATC usage), plus it is capable of displaying a five character fix or route name and a four digit time-of-day. In this manner holding fixes, routes, fix departure times, etc., may be communicated without usage of voice channels. Presumably, certain of these messages would require use of pilot response pushbuttons on the transponder. Control over the sixteen message displays (thirty-two if ground control messages are counted) is accomplished with data items two, three and four; item two instructs to update or clear the display, and items three and four indicate which display is to be updated or cleared. Update or clearing of the fix name and time displays are controlled by the airborne equipment, i.e., fix names are always associated with certain messages and times with others. For example, the fix name would always be updated when a holding instruction is issued, but would not be affected when a takeoff clearance is issued. The name would then be cleared when the holding message was cleared, or would be updated when another message causes it to be activated.

Alphanumeric Data (Function #4): This display is intended for communication of clearance data and other information in a free, thirty-two character format rather than as fixed standard messages (above). This concept was presented in Reference 12. The data is transmitted in one to four eight character blocks, one block per DABS frame. Data items two and three control display operation; item four contains the address (one through four) of the section to be updated; item five contains eight characters of data. Item two is used to clear the display and memory. Item three is used to blank the display but activate memory, and then activate the display after all data has been sent.

RNAV Tactical Control Amendment (Function #5): This message is the RNAV equivalent to the tactical radar vector. Either a dedicated display could be used, or the display could be integrated with the RNAV computer and could allow direct input of impromptu waypoint data to the RNAV. This message normally requires one DABS frame; however, an additional frame is transmitted when waypoint identification data is required. The waypoint can be identified by name, by VOR/Rho/Theta or by Latitude/Longitude. Waypoint name would by far be the most common, and would refer to published waypoint names. Only in those cases where previously undefined impromptu waypoints are required (possibly certain metering and spacing procedures) would waypoint coordinates be transmitted.

The functions provided by this RNAV message include a parallel offset command, a "direct-to" command, a resume route navigation command, a sequencing turn command, a fan command, an arrival time command, and a time synchronization message. Ordinary radar vector messages may be used in conjunction with this message, particularly for purposes of transmitting altitude messages. Data item number four is simply a parallel offset command. Item five is a "direct-to-waypoint" command and would be followed by the tag frame containing waypoint identification. Note that provision is made in this command for a turn cue when the turn required is significant (greater than 30°). This would allow immediate initiation of the turn while entering the objective waypoint identification in the RNAV computer. Item six is a command to cease the offset or fan maneuver and reacquire the standard route track. This would normally follow those commands. The sequencing turn command specifies a distance before or after the waypoint at which to initiate turn to the next waypoint. This would be used for executing trombone maneuvers and certain M&S pattern maneuvers. The x^o command calls for a departure from track at the indicated departure bearing from track. This is typically followed by a resume navigation command. When field ten is set to zero and a time value (field nine) is given, it is interpreted to specify the arrival time for the waypoint given in the tag frame. When field ten is set to one and a time value is given, that time is present time-of-day, and should be used to set the local clock. No tag frame would be transmitted.

When the tag frame is transmitted, field five contains either waypoint name or coordinates, depending on the setting of field four. If coordinates are to be transmitted, the ATC system must have prior knowledge of which coordinate system to use, Rho/Theta or Lat/Lon. Ways of accomplishing this are discussed in a later section. The tag frame also contains waypoint altitude for use when more appropriate than a radar vector altitude message.

MLS Data Monitoring Technique

MLS approach data monitoring is considered as a candidate method for reducing independent parallel runway separation. The MLS data, being quite accurate, would complement radar data. Furthermore, blunder detection and prevention would be accomplished through detection of improper MLS guidance signals aboard the aircraft being monitored. The monitor would be accomplished through a direct link of the MLS unit with the DABS transponder. Monitor replies would be elicited by the ground radar through a normal interrogation containing the MLS unit address in the "Air-to-Ground Data Link Message Source" field (see Reference 3).

MLS Approach Monitor (Function #11): Provision is made in this air-to-ground message for azimuth, elevation and range data relative to the antenna site. These data are natural binary or offset binary format, which would probably be the types generated by an MLS sensor. Furthermore, sensor indicators are provided. Field six allows for the selection of approach or flare guidance. Field seven allows reporting of marker beacon passage. Field eight indicates reception of back course guidance. Field nine automatically reports the primary MLS channel tuned, to prevent ambiguity.

Optional RNAV Message Services

This section discusses additional services to RNAV-equipped aircraft which could be provided through use of the DABS data link. Both of these services involve the delivery of route waypoint data through the DABS data link directly into the airborne RNAV computer. The first such service would serve to significantly reduce data insertion errors and pilot workload at critical times for those aircraft not equipped with bulk flight plan data storage and recall capabilities, which would include most private, corporate and commuter airline instrument operators. The service would be available for those who file IFR flight plans, and would include automated delivery of data for the filed enroute segment, as well as data for the departure and arrival segments selected by ATC. The service shall be referred to as Route Data Delivery (RDD), and includes two types of messages: an Air/Ground data request and a Ground/Air data delivery message. This service would apply for charted RNAV routes or for preplanned direct routes where standard route segments or waypoints are used. The other service described here involves more automation improvements than simply a DABS data hookup, although the data delivery aspect is similar. This service would be intended to provide route waypoint information, considering station coverage, restricted areas and minimum enroute altitudes, for preplanned direct flight where only the origin and destination (and intermediate points if desired) are specified, but other waypoints along the route are required to provide for navigation station coverage. This service obviously would require an additional software capability to generate those intermediate waypoints, considering existing station coverage data. Such a service may be provided by the Flight Service System. The messages presented here include Air/Ground data requests which could be used either for prefiled IFR routes or air-filed VFR routings. The Ground/Air data transmittal is identical to the RDD above. Finally, a message is discussed which could be used to provide (automatically) detailed aircraft type and avionics complement data to the ATC system upon request. This message could be used to replace the necessity for supplying such data manually when filing a flight plan, and so could speed up the flight planning process.

RNAV Route Data Request (Function #6): This message is used for requesting automated transmission to the RNAV computer of waypoint data for a prefiled route or for departure or arrival segments assigned by ATC (SID/STAR data). It is intended expressly for those operators not equipped with a flight plan data base from which to select such data by route or procedure name. All of the RNAV messages discussed below would have the same device address, although the message type indicators would be different. Data item three of this message indicates whether the request is for a prefiled flight plan or for a route to be flown VFR. If it is a VFR request, the route identification number would be supplied in field eight. Fields four through six indicate the type of request, i.e., initial request for data, request for next set of data, or a repeat request for data checking. Field seven gives the maximum number of waypoints to be transmitted. Note that this service would be suitable for all users, whether they be equipped with single waypoint systems or systems capable of storage of many waypoints. This message initiates transmittal of the RDD messages, below.

Route Data Delivery (Functions #7 and #8): These two message provide the RDD function in either the Rho/Theta (7) format or the Lat/Lon (8) format. Each message consists of two DABS frames for each waypoint transmitted. The first frame in each case starts by listing the waypoint name in field four. The Rho/Theta format follows with those parameters in fields five and six. The second frame then contains VOR Ident and Frequency in fields four and five. Waypoint altitude and inbound track angle are contained in fields six and seven. Note that it was necessary to resort to an altitude resolution of five hundred feet in order to fit all the data in the two frames. This is suitable for all phases of flight except final approach (which would require a twenty foot resolution not provided by any of these messages), and so does not significantly compromise the utility of the message.

The Lat/Lon format message is organized so that the latitude takes up the remainder of the first frame. The second frame contains longitude (field four), associated VOR frequency (field five) and altitude (field six).

Airborne Filing--Direct Route Clearance (Function #9): This message allows filing of an IFR direct flight plan amendment, or allows VFR aircraft to specify a direct route such that ATC would provide waypoint data along that route upon request. This message requires two DABS frames, the first of which would contain the origin waypoint identifier, the filed enroute altitude, and an indication of whether this is an IFR amendment or VFR request (fields four, five and six). The second frame contains the destination waypoint and filed airspeed in fields four and five.

Direct Route Data Request (Function #10): This message is related to the route data request (6), except it is much simpler. Only the waypoint sequence number (00 is origin waypoint) of the first waypoint to be transmitted and the number of waypoints need be specified. ATC would assign unique names to each waypoint which would consist of three characters and two digits. The three characters would be unique to that flight that day and the two digits would constitute the waypoint sequence number. The origin and destination waypoints would retain their original designations. Upon execution of the data request, the data would be furnished through the RDD function (functions 7 and 8).

Capability Report (Function #12): This capability report message could optionally be provided as a means of simplifying the flight planning procedure. It would be transmitted upon request of ATC, and would provide information helpful to controllers, to the Metering and Spacing function and for providing the RNAV data services discussed above. In particular, the DABS message display capabilities of each aircraft would be described in detail through this message, which would simplify and facilitate operation of the DABS control message automation delivery function. The message would be delivered by a simple hard-wired device easily tailored to each individual aircraft; no pilot intervention would be required for the use of the device. Most of the fields in this message are sufficiently explained in Table A.4. It should be added that the purpose of field three, aircraft type, is to provide aircraft weight and speed class data for the M&S system. Also, field nine provides for non-ELM displays of types other than those discussed here.

Table A.1 Standard Control Messages

ENVIRONMENT Term.	ENVIRONMENT Enrt.	LINK G/A	LINK A/G	FUNCTION No	FUNCTION NAME	DATA ITEM No	DATA ITEM Name	RANGE	RESOLUTION	CODE	BITS	TOTAL	COMMENTS
x	x	x		1	Radar Vector	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
					(with optional data tag)	2	Frame Number			1b	1		bit=0
					ATC Control and IPC	3	IPC Indicator			1b	1		bit=0 Control Vector; bit=1 IPC Vector
						4	Clear Display			1b	1		bit=0 Update Display; bit=1 Clear Display
						5	Heading Update			1b	1		bit=0 No Change; bit=1 Update/Clear
						6	Speed Update			1b	1		bit=0 No Change; bit=1 Update/Clear
						7	Altitude Update			1b	1		bit=0 No Change; bit=1 Update/Clear
						8	Comm. Freq. Update			1b	1		bit=0 No Change; bit=1 Update/Clear
						9	Baro. Update			1b	1		bit=0 No Change; bit=1 Update/Clear
						10	Speed Range			2b	2		bit1=0 None; bit1=1 Range Present
						11	Alt. Range			2b	2		bit2=0 Below; bit2=1 Above
						12	Heading	1- 360	1°	3d	12		Straight BCD Code Used; best for
						13	Speed	0- 999	1kt	3d	12		lowest capability display
						14	Altitude	0- 999	100ft	3d	12		
						15	At or Below			1b	1		bit=0 At; bit=1 At or Below
						16	At or Above			1b	1		bit=0 At; bit=1 At or Above
						17	Spare			2b	2	56	
					Optional Tag Frame	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
					(additional data)	2	Frame Number			1b	1		bit=1
						3	Comm. Freq.	18.000-35.975	.001MHZ	5d	17		100MHZ Presumed; #1bit in last digit set=0
						4	Baro. Setting	28.00- 32.00	.01in.Hg	4d	13		#3bit in first digit presumed set=1
						5	Other Speed	0- 399	1kt	3d	10		399 implies unlimited
						6	Other Alt.	0- 799	100ft	3d	11	56	799 implies unlimited
x	x	x		2	Proximity Warning Indicator	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
						2	Clear Display			1b	1		bit=0 Update; bit=1 Clear Light
						3	Steady/Flash			1b	1		bit=0 Steady, bit=1 Flash
						4	PWI			36b	36		12x3 PWI lights
						5	IPC Command			9b	9		5 crosses, 4 arrows
						6	Spare			5b	5	56	
x	x	x		3	Precoded ATC Clearance Messages	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
						2	Clear Display			1b	1		bit=0 Update, bit=1 Clear Message
						3	Air/Ground			1b	1		bit=0 ATC Message; bit=1 Ground Control
						4	Coded Messages			4b	4		Sixteen Messages Possible
						5	Fix Name			5c	30		Clearance Limit; Holding Fix; etc.
						6	Time of Day			4d	16	56	(HH MM) EFC Time; Depart Fix; etc.
x	x	x		4	Alphanumeric Data (32 Char. in 8 Char. Segments) (FAA-RD-74-62)	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
						2	Clear Display			1b	1		bit=0 No Action; bit=1 Clear All
						3	Display Enable			1b	1		bit=0 Blank; bit=1 Display On
						4	Section Address			2b	2		Section 1 through 4
						5	Data			8c	48	56	Eight Characters of Data

Table A.2 Standard RNAV Message

ENVIRONMENT		LINK		FUNCTION		DATA ITEM		RANGE	RESOLUTION	CODE	BITS	TOTAL	COMMENTS
Term	Enrt.	G/A	A/G	No.	Name	No.	Name						
x	x	x		5	RNAV Tatical Control Amendment (M&S and ATC Usage--can be used in conjunction with Radar Vector message)	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
						2	Message Type			2b	2		Unique to This RNAV Message
						3	Frame Number			1b	1		bit=0
						4	Offset	±19	1mi	2d	6		Parallel Offset (Left/Right)
						5	Direct To			3b	3		bit1=0 No Direct; bit1=1 Direct To; bit2=0 No Turn; bit2=1 Turn Cue; bit3=0 Left; bit3=1 Right.
						6	Resume Nav			1b	1		bit=0 Continue Procedure; bit=1 Resume Nav.
						7	Turn at x Miles	±79	1mi	2d	8		Start Sequence Turn at x Miles (To/From)
						8	Fan X°	±79	1°	2d	8		Start Fan X° From Track (Left/Right)
						9	Time	23 59 59	1sec	6d	22		(HH MM SS) 40 Time Command
						10	Set Clock			1b	1	56	bit=0 Time Command; bit=1 Synchronization
x	x	x			Optional Tag Frame	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
						2	Message Type			2b	2		Same As Above
						3	Frame Number			1b	1		bit=1
						4	Name/Data			1b	1		bit=0 Name; bit=1 Waypoint Data
						5	Waypoint Name			5c	30		bits 9 through 45 contain either
							Spare			7b	7		Waypoint Name or Coordinates.
						5'	VOR Freq.	08.20 - 17.95	.01MHZ	4d	13		100MHZ Presumed
							Rho	0 - 199	1mi	3d	9		
							Theta	1 - 360	1°	3d	10		VOR/Rho/Theta
							Spare			5b	5		
						5"	Latitude	0- 79 59.9	.1'	5d	18		Lat/Lon; bits#1 of ten's digit of degrees
							Longitude	0-179 59.9	.1'	6d	19		and minutes presumed set=0
						6	Altitude	0 - 799	100ft	3d	11	55	

Table A.3 Route Data Delivery Messages

ENVIRONMENT Term.	ENVIRONMENT Enrt.	LINK G/A	LINK A/G	FUNCTION No.	FUNCTION Name	DATA ITEM No.	DATA ITEM Name	RANGE	RESOLUTION	CODE	BITS	TOTAL	COMMENTS
x	x		x	6	RNAV Route Data Request	1	DADR			4b	4		Originating Device Address
					(Request Waypoint Data	2	Message Type			4b	4		Unique to This RNAV Message Type
					for Prefiled Route or	3	Prefiled			1b	1		bit=0 Prefiled Route; bit=1 VFR Request
					VFR Routing)	4	Initial Request			1b	1		bit=1 Request First Set of Waypoints
						5	Next Data			1b	1		bit=1 Request Next Set of Waypoints
						6	Repeat Data			1b	1		bit=1 Repeat Last Set of Waypoints
						7	Waypoints	1 - 15		4b	4		Waypoints per Set (=0 Send Entire Route)
						8	Route ID			4d	16		If Route Not Prefiled
						9	Spare			24b	24	56	
x	x	x		7	Route Data Delivery (RDD)	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
					Rho/Theta RNAV	2	Message Type			2b	2		Unique to this RNAV Message
					(Two Frames Per Waypoint)	3	Frame Number			1b	1		bit=0
						4	Waypoint Name			5c	30		
						5	Rho	1 - 199	1mi	3d	9		
						6	Theta	1 - 360	1°	3d	10	56	
					Second Frame	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
						2	Message Type			2b	2		Same As Above
						3	Frame Number			1b	1		bit=1
						4	VOR ID			3c	18		
						5	VOR Freq.	08.20-17.95	0.01MHZ	4d	13		100MHZ Presumed
						6	Altitude	0 - 795	500ft	3d	8		one bit in hundreds (feet) represent 500 ft.
						7	Track Angle	1 - 360	1°	3d	10	56	
x	x	x		8	Route Data Delivery (RDD)	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
					Lat/Lon RNAV	2	Message Type			2b	2		Same as Rho/Theta RDD
					(Two Frames Per Waypoint)	3	Frame Number			1b	1		bit=0
						4	Waypoint Name			5c	30		
						5	Latitude	0- 79 59.9	0.1'	5d	19	56	
					Second Frame	1	AR/DADR			4b	4		Acknowledgement Request/Device Address
						2	Message Type			2b	2		Same As Above
						3	Frame Number			1b	1		bit=1
						4	Longitude	0-179 59.9	0.1'	6d	21		
						5	VOR Freq	08.20-17.95	0.01MHZ	4d	13		100MHZ Presumed
						6	Altitude	0 - 799	100ft	3d	11		
						7	Spare			4b	4	56	

Table A.4 Direct Route and Miscellaneous Messages

ENVIRONMENT Term.	Enrt.	LINK G/A	A/G	FUNCTION No.	Name	DATA ITEM No.	Name	RANGE	RESOLUTION	CODE	BITS	TOTAL	COMMENTS
x	x		x	9	Airborne Filing Direct Route Clearance (Two Frames Req'd)	1	DADR			4b	4		Originating Device Address
						2	Message Type			4b	4		Unique to This RNAV Message Type
						3	Message Frame			1b	1		bit=0
						4	Origin Waypoint			5c	30		if blank, present position presumed
						5	Filed Altitude	0 - 999	100ft	3d	12		
						6	VFR/IFR			1b	1		bit=0 VFR; bit=1 IFR Reclearance
						7	Spare			4b	4	56	
					Second Frame	1	DADR			4b	4		Originating Device Address
						2	Message Type			4b	4		Same As Above
						3	Message Frame			1b	1		bit=1
						4	Destination WP			5c	30		
						5	Filed Airspeed	0 - 999	1kt	3d	12		
						6	Spare			5b	5	56	
x	x		x	10	Direct Route Data Request (Note: Data sent by RDD; waypoint names are XXXNN where X's are arbitrary three characters assigned and N's are WP Seq. No.)	1	DADR			4b	4		Originating Device Address
						2	Message Type			4b	4		Unique to This RNAV Message Type
						3	WP Sequence No.	0 - 99		2c	12		Identifies First Waypoint in Set
						4	Waypoints	1 - 15		4b	4		Waypoints per Set (=0 Send Entire Route)
						5	Spare			32b	32	56	
x			x	11	MLS Approach Monitor	1	DADR			4b	4		Originating Device Address
						2	Message Type			1b	1		Unique to This MLS Message Type
						3	Azimuth	±100	.05°	12b	12		Natural Binary
						4	Elevation	0 - 50	.05°	10b	10		Natural Binary
						5	Range	0 - 40	.01nmi	12b	12		Natural Binary
						6	Sensor			2b	2		Select Sensor Data Reported
						7	Marker Beacon			2b	2		bits=0 None; =1 Outer; =2 Middle; =3 Inner.
						8	Back Course			1b	1		bit=0 Front Course; bit=1 Back Course
						9	Freq. Channel	200		3d	12		Select Channel Data Reported
x	x		x	12	Capability Report (Transmitted after receipt of request)	1	DADR			4b	4		Originating Device Address
						2	Message Type			4b	4		Unique to This Message
						3	Aircraft Type			4b	4		Arbitrary Type Classifications
						4	Coded ATC-Air			1b	1		bit=1 Precoded Clearance Capability
						5	Coded ATC-Gnd.			1b	1		bit=1 Precoded Clearance Capability
						6	Radar Vector Tag			1b	1		bit=1 Extended Vector Capability
						7	RNAV Control			1b	1		bit=1 RNAV Tactical Control Display
						8	Alphanumeric			1b	1		bit=1 Alphanumeric Display (32 char.)
						9	Other Displays			6b	6		Indicates Types Available
						10	ILS			1b	1		bit=1 ILS Capability
						11	MLS			1b	1		bit=1 MLS Capability
						12	MLS Link			1b	1		bit=1 MLS Approach Data Link
						13	RNAV			1b	1		bit=1 RNAV Capability
						14	Type RNAV			1b	1		bit=0 Rho/Theta; bit=1 Lat/Long
						15	VNAV			1b	1		bit=1 VNAV Capability
						16	4D RNAV			1b	1		bit=1 4D RNAV Capability
						17	RNAV Link			1b	1		bit=1 RNAV Data Link Capability
						18	VOR Data Base			1b	1		bit=1 Data Base Capability
						19	WP Data Base			1b	1		bit=1 Data Base Capability
						20	Spare			23b	23	56	

A.3 DABS DATA LINK CAPACITY REQUIREMENT IMPACT

INTRODUCTION

The objective of this analysis is to quantify the impact which RNAV implementation will have upon Discrete Address Beacon System Data Link usage and Data Link System Capacity. It should be noted at the outset that the principal constraint on DABS surveillance and data link system capacities is not a function of the DABS signal format itself, but of the automated aircraft tracking, data handling and interrogation scheduling equipment which will be used to control DABS operation. Also, the capacities of the data channels connecting the DABS site computers with NAS and ARTS computers, and those computers themselves, limit DABS capacity.

If otherwise unconstrained by interleaved ATCRBS interrogations, a DABS sensor is capable of completing 6660 interrogation/reply pairs per second, or 74 interrogations per degree of scan, based on a four second scan period (equations from Reference 3). If all aircraft were evenly spaced, 26640 could be tracked by a single DABS site, although normal bunching of aircraft azimuths would reduce this value in practice. Based upon analysis of the projected 1995 environment in the Los Angeles basin, a peak count of 1700 aircraft would be tracked at any one time, and this would be accomplished by four or more sites [7]. The resulting interrogation rate [7] would be 643 interrogation replies per second, total for all sites. This would form the basis of the actual capacity requirement for the automated equipment used to control DABS operation and track aircraft. If Synchro-DABS capability is to be supported, as expected, the number of interrogation replies would double (for the same number of tracked aircraft), since a synchronized reply would be transmitted by each aircraft upon each antenna scan. Theoretical DABS tracking capacity is reduced somewhat further by Synchro-DABS since the synchronized replies must be transmitted at certain points in time (epochs). However, the DABS signal saturation point still far exceeds any possible foreseen traffic load.

The addition of data link capability to the DABS function increases the reply message length from 64 to 120 microseconds for those DABS signals which contain messages. However, any standard data link transmission (either air/ground or ground/air) may also serve as either a tracking interrogation reply or synchronization reply. Therefore, with a few exceptions to be discussed later, data link does not necessarily require more messages, only that some messages be of longer duration. The preceding is not true for the DABS Extended Length Message (ELM) capability, where a special format message with higher data content is used for transmitting larger volumes of data to specially equipped aircraft on a lower-priority basis.

This analysis shall consider an earlier assessment of required DABS system capacity [7], update it for recent developments in message format and usage, and then determine the degree of change in DABS support automation capacity required providing that RNAV is implemented as the primary navigation system. In addition, the added impact of supporting an optional RNAV feature, Route Data Delivery (RDD), is determined.

ANALYSIS

Data presented in Reference 7, "ATC Performance Requirements for Developing Prototype Versions of the Discrete Address Beacon System", is used as the basis of this study. In that reference, the 1995 Los Angeles Basin traffic model developed for use in the Air Traffic Control Advisory Committee report [13] was used, although that traffic model was further broken down to identify those numbers of aircraft actually arriving/departing LAX airport, those on final approach, those IFR, those in positive controlled airspace, those in mixed airspace and VFR aircraft in TCA's. The L.A. Basin dimensions are 60 x 120 miles, and it would be expected that four or more DABS sites would serve the area. Also in Reference 7 the basic coverage, surveillance range and accuracy and update rates, and basic data link performance requirements are discussed as they apply to each of the segments of traffic identified earlier. The analyses included requirements for Intermittent Positive Control (IPC) system performance.

In Reference 7, five tables of data of interest to this analysis are presented; these tables, labeled Table 3-3 through 3-7 in that report, are reproduced and attached at the end of this discussion. They were derived under the presumption that present navigational practices would be continued into the 1995 time period; this was not intended to exclude RNAV, but merely to maintain a conservative point of view on the presumption that RNAV would result in a lower overall data link capacity requirement. The first step in the present analysis has been to review the results presented in those tables based upon recent developments, including firm definition of DABS basic signal formats and interchange protocol [12], and development of candidate data link message formats (Section A.2). New tables have been developed as a result. The only significant differences are as a result of (1) the fact that separate messages were used to transmit heading, airspeed, and altitude data, and altimeter setting and communications frequency data in the earlier report, whereas these have been combined into single messages in the later analysis, and (2) the fact that certain messages have been found to require two DABS transmission frames rather than one, as presumed earlier. The revised tables are presented below; each is discussed in order that the differences with the original tables may be explained. Each is followed with the equivalent table given that RNAV is implemented, so that a direct comparison of the RNAV effect may be made.

LAX Arrivals and Departures

The changes made in the original table (3-3) are shown in Table A.5, where altitude, heading and speed have been combined into a Radar Vector message and communication frequency and altimeter setting are combined. In Reference 7, the number of enter and leave holding pattern messages were taken to be equal to the percent of arrival aircraft holding (25%), whereas it is felt to be more realistic to treat most of the arrivals as having been held at one time or another if that many aircraft are in the holding pattern, and so 0.75 such messages per arrival, rather than 0.25, are presumed. The results shown in Table A.5 indicate a significant savings in message rate over the earlier study described in Reference 7. The footnotes to the table explain changes made to Table 3-3, Reference 7.

Table A.5

Uplink Message Rates - IFR Arrivals and Departures

LAX TCA (No RNAV)

Message	Messages/AC		Frames Per Message	Minutes in Control	Messages/AC/Minute	
	ARR	DEP			ARR	DEP
Radar Vector[1]	8	3	1	20	0.40	0.15
Comm. & Alt. Set.[2]	2	2	2	20	0.20	0.20
Route or Runway	1	1	1	20	0.05	0.05
Ground Control	3	4	1	20	0.15	0.20
Enter Hold	.75	-	1	20	0.04	—
Leave Hold	.75	-	1	20	0.04	—
				Total	0.88	0.60
Reference 2, Table 3-3					1.09	0.70

[1]Fourteen individual arrival messages conbined into eight, six departures messages into three.

[2]Three arrival and departure messages combined into two.

Table A.5-R

Uplink Message Rates - IFR Arrivals and Departures

LAX TCA (100% RNAV)

Message	Messages/AC		Frames Per Message	Minutes in Control	Messages/AC/Minute	
	ARR	DEP			ARR	DEP
SID/STAR	1	1	1	20	0.05	0.05
RNAV Amendment	1	-	1	20	0.05	—
Radar Vector	3	1	1	20	0.15	0.10
Comm. & Alt. Set.	2	2	2	20	0.20	0.20
Route or Runway	1	1	1	20	0.05	0.05
Ground Control	3	4	1	20	0.15	0.20
Enter Hold	.75	-	1	20	0.04	—
Leave Hold	.75	-	1	20	0.04	—
				Total	0.73	0.60

The results of an equivalent analysis using, wherever possible, RNAV procedures are shown in Table A.5-R. In that table the eight arrival radar vectors are replaced with a STAR route message, one RNAV route amendment for sequencing purposes and three radar vectors. The vectors are for speed changes not shown on the STAR procedure, and the final sequencing turn onto the approach course. Similarly, the three departure radar vectors are replaced by a SID message and one vector. Of the message rates which result, in the arrival case it is lower, while in the departure case the rate is the same. Therefore, as expected, the use of RNAV procedures helps the situation rather than hurting it.

Enroute Operations Above 10,000 Ft

The changes made in the original table (3-4) are shown in Table A.6, where altitude, heading, speed and frequency assignments are combined into radar vector messages of one frame length (alt., heading, speed) and two frames length (including communication frequency). Other data remains as before. The results do not differ significantly with the earlier analysis [7], with some message rates being higher and some lower. The results of the equivalent RNAV analysis are presented in Table A.5-R; slight reductions in overall message rate resulted from the replacement of some radar vector messages with RNAV control messages. The RNAV messages are the SID/STAR route message and RNAV Route Amendment message. The remaining radar vectors are for speed changes and communication frequency updates.

VFR Aircraft in TCA

The changes made in the original table (3-5) of Reference 7 are shown in Table A.7. Again, altitude, heading, speed, frequency and altimeter setting messages are combined into one-and two-frame radar vector messages. IPC advisories were also estimated for this case; the values used are the same as were derived in the earlier analysis. The results of an equivalent RNAV analysis are shown in Figure A.7-R, where a slight reduction in message rate results.

Total Average Uplink Message Rate

The résults in Tables A.5, A.6 and A.7, plus the results of an IPC message rate analysis from Reference 7 (which refers to Reference 14), are summarized in Tables A.8 and A.8-R. These results should be compared with Table 3-5 from Reference 7. These tables include the absolute numbers of aircraft in each category of use, such that the overall message rate may be estimated. The IPC message rate estimates in Table 3-5 are based upon Reference 14. It should be understood that these estimates presumed that the IPC messages would be repeated in every scan. However, this repetition should not be necessary according to the way the DABS is now structured. To convert the repetitive message rates given (PWI-6 aircraft per minute; Positive Control -0.8 per aircraft per minute) to one-shot messages followed by a cancellation message when the threat is over, it was presumed that each PWI situation lasts an average of 2 minutes before change or cancellation, while the positive control situation would last 1 minute (based upon the thirty second threat criteria). Presuming an average scan repetition rate of 4 seconds, new values for PWI alert/cancel message rate and for Positive Control control/cancel message rate of 0.40 and 0.11 messages per minute were derived. These are the values used in Tables A.8 and A.8-R. Furthermore, refinements in the PWI and IPC threat-evaluation techniques currently under development should reduce these values even more. It should be noted that the IPC message rates shown in Table A.8 are relatively large compared to ATC message rates only because there

Table A.6

Uplink Message Rates - IFR Enroute
Above 10,000 ft. (No RNAV)

Message	Frames Per	Arrivals	Departures	Overs	Withins
Radar Vector	1	4.5	2.0	0.5	4.0
Vector with Comm Freq.	2	2.5	2.5	3.4	3.0
Route or Runway	1	1.0	1.0	-	2.0
Route Changes	1	0.2	0.3	0.2	0.4
Total Frames		10.7	8.3	7.5	12.4
Control Life		33.1	40.2	59.3	46.8
Messages/AC/Minute		0.32	0.21	0.13	0.26
% Traffic		34.9	24.8	16.3	24.0
Overall Average			0.24		0.26
Reference 2, Table 3-4			0.26		0.32

Table A.6-R

Uplink Message Rates - IFR Enroute
Above 10,000 ft. (100% RNAV)

Message	Frames Per	Arrivals	Departures	Overs	Withins
SID/STAR	1	1.0	1	-	2.0
RNAV Amendment	1	1.0	-	-	1.0
Radar Vector	1	0.8	-	-	0.2
Vector with Comm. Freq.	2	2.5	2.5	3.4	3.0
Route or Runway	1	1.0	1.0	-	2.0
Route Changes	1	0.2	0.3	0.2	0.4
Total Frames		9.0	7.3	7.0	11.6
Messages/AC/Minute		0.27	0.18	0.12	0.25
Overall Average			0.21		0.25

Table A.7

Uplink Message Rate - VFR Aircraft
in TCA and VFR Highways (No RNAV)

Message	Frames Per	Messages/AC	Minutes	Messages/AC/ Minute
Radar Vector	1	2	20	0.10
Vector with Comm. & Alt.	2	1	20	0.10
IPC	1	2	20	0.10
Total				0.30
Reference 2, Table 3-5				0.40

Table A.7-R

Uplink Message Rate - VFR Aircraft
in TCA and VFR Highways (100% RNAV)

Messages	Frames Per	Messages/AC	Minutes	Messages/AC/ Minutes
RNAV Amendments	1	1	20	0.05
Vector with Comm. & Alt.	2	1	20	0.10
IPC	1	2	20	0.10
Total				0.25

is so much traffic. ATC messages are roughly proportional to traffic density, while PWI/IPC messages are roughly proportional to the square of traffic density, since airspace conflicts tend to exhibit such behavior (see mass flow analogy in Reference 15).

As may be seen by comparing Table A.8-R with A.8, the use of RNAV reduces the number of ATC-related messages by 0.5 messages per second (12%), along with which there should be an equivalent reduction in the complexity of the computer hardware required to receive, schedule and monitor transmission of such messages. Since, as stated before from Reference 7, the average DABS interrogation rate is 643 interrogations per second, the added burden on DABS channel usage of 13 messages per second is negligible. This is particularly true since most such messages will be transmitted as a part of the standard tracking or synchronization interrogation (Note: if Synchro-DABS is implemented, the 643 interrogations from [7] nearly doubles).

Extended Length Messages

In Reference 7, the subject of Extended Length Message service is analyzed from both the points of view of extended ATC service messages and company messages. It concludes that a reasonable mean ELM data rate for the 1995 peak traffic period would be 156 characters per second. Since the ELM format provides for an 80 character data block [12], two additional DABS messages per second would be required to provide such service. Thus the total message count would be 15 (non-RNAV or 14.5 (RNAV).

Downlink Messages

DABS response messages fall in four basic categories: Surveillance Responses (not of concern here), Technical Acknowledgements (the return of uplinked data to the ground for error detection), MLS Position Reports (an optional capability to provide for closely-spaced parallel runway monitoring), and Pilot Requests. In addition, Reference 7 erroneously lists pilot acknowledgement of IPC and ATC commands or requests as being downlink messages; according to present formats, these data are transmitted as bit settings in the normal interrogation response message, which is not a data link message. All uplink messages receive technical acknowledgements, so this contributor to total downlink messages is already defined. Reference 7 estimates that the pilot requests for data will occur at the rate of three times per hour per aircraft (0.4 messages per second overall). While this is probably rather high, it is small in comparison to the other numbers and so will not be changed here. Reference 7 also estimates that 12 messages per second would be received due to the MLS monitor feature. This would result from monitoring three aircraft on each of the four approach paths presumed to exist in 1995, with an update rate of once per second. This value (12/second) is large compared to the other message frequency (13/second-all services). This may be necessary to achieve a higher degree of control to allow very close runway spacing. It should be recognized that this is an exceptional service; only one of the DABS sites in the area would be required to support it. Presumably, special processing equipment would be developed for monitoring the approaches. Total downlink requirements are summarized in Table A.9.

Table A.8

Total Average Uplink Message Rate
1995 Peak Traffic, LAX Basin (No RNAV)

Aircraft Category	From Table	Messages/AC/ Minute	Number of AC	Messages Per Second
IFR Arrivals	A.5	0.88	67	1.0
IFR Departures	A.5	0.60	67	0.7
IFR Holds	A.5	0.25[1]	16	0.1
GA Overflights	A.6	0.24	280	1.1
IFR Withins	A.6	0.26	50	0.2
PWI Advisories	*	0.40	1010	6.7
IPC Commands	*	0.11	1010	1.9
VFR in TCA	A.7	0.30 (0.20 ATC) (0.10 IPC)	265	1.3 (0.9 ATC) (0.4 IPC)
Total				13.0 4.0 ATC 9.0 IPC
Reference 2, Table 3-6				118.7 4.8 ATC 113.7 IPC

[1]It was presumed that each holding aircraft would receive an altitude reclearance every four minutes.

*These values were taken from the text.

Table A.8-R

Total Average Uplink Message Rate
1995 Peak Traffic, LAX Basin (100% RNAV)

Aircraft Category	From Table	Messages/AC/ Minute	Number of AC	Messages Per Second
IFR Arrivals	A.5-R	0.73	67	0.8
IFR Departures	A.5-R	0.60	67	0.7
IFR Holds	A.5-R	0.25[1]	16	0.1
GA Overflights	A.6-R	0.21	280	1.0
IFR Withins	A.6-R	0.25	50	0.2
PWI Advisories	*	0.40	1010	6.7
IPC Commands	*	0.11	1010	1.9
VFR in TCA	A.7-R	0.25 (0.15 ATC) (0.10 IPC)	265	1.1 (0.7 ATC) (0.4 IPC)
Total				12.5 3.5 ATC 9.0 IPC

1-* (see Table A.8 for notes)

Table A.9 Downlink Message Rates 1995 Peak Traffic, LAX Basin

Message Type	Messages/Second
Technical Acknowledgment*	13.0 (12.5 RNAV)
Pilot Requests	0.4
MLS Position Report	12.0
TOTAL	25.4 (24.9 RNAV)

*/Note/ ELM messages are not technically acknowledged

Route Data Delivery Option

Route Data Delivery (RDD) is an optional capability which could be used for distributing waypoint data to equipped aircraft automatically upon request of the airborne DABS unit. It would serve as a substitute for an airborne data base in the RNAV system, or manual input of waypoint parameters. The impact of RDD on DABS channel usage obviously depends upon the number of aircraft which would use this service. It was assumed for present purposes that 50% of all IFR aircraft would use it. The cases of the TCA arrivals/departures, which would use standard SID/STAR procedures, and of other IFR operations, which would use ordinary enroute transitions to approach procedures and standard departures to enroute waypoints, are considered separately.

TCA Arrivals/Departures

An uplink rate of 0.6 messages/AC/minute for the SID/STAR data results from an assumption that each procedure contains six waypoints, and each waypoint requires two DABS frames, and each aircraft is under control for twenty minutes. Presuming 50% participation of the 67 arriving aircraft:

TCA Uplink Rate = 0.3 Messages/Second

The downlink rate for data requests in this case is negligible.

Other IFR Operations

The uplink message rates for the other 330 IFR aircraft were arrived at through the following presumptions:

- Basin Dimensions = 60 x 120 nm
- Waypoint Spacing = 40 nm
- Approach Waypoints = 3
- Departure Waypoints = 2

The results are presented in Table A.10.

Table A.10 Non-TCA IFR Uplink Rates - RDD

Category	Waypoints				Control Life	Frame	Msg/AC/Min	% Traffic	Overall Average
	Route	Appr	Dep	Total					
Arrival	1.5	3	-	4.5	33.1	2	0.27	34.9	0.20
Departure	1.5	-	2	3.5	40.2	2	0.17	24.8	
Overs	3.0	-	-	3.0	59.3	2	0.10	16.3	
Withins	1.5	3	2	6.5	46.8	2	0.28	24.0	0.28

Category	Overall Average	Number Aircraft	Participation	Messages Per Second	Total
Arrivals Departures Overs	0.20	280	50%	0.5	
Withins	0.28	50	50%	0.1	0.6

The downlink message rates are based upon the following presumptions for number of data requests:

- Arrivals = 0.5 for route + 1.0 for approach
- Departures = 1.0 for departure + 1.0 for route
- Within = 1.0 for departure + 1.0 for approach
- Overs = 0.5 for route

The 0.5 values for route data presume that in many cases such data will have already been delivered before entering the LAX area. The results are presented in Table A.11 (one frame per message), using other data (control life, etc.) from Table A.10.

Table A.11 Non-TCA IFR Downlink Rates - RDD

Category	Messages				Msg/AC /Min	Overall Average	Msg.Per Second	Total
	Route	Appr.	Dep.	Total				
Arrivals	0.5	1	-	1.5	0.05	0.04	0.1	
Departures	1	-	1	2.0	0.05			
Overs	0.5	-	-	0.5	0.01			
Withins	-	1	1	2.0	0.04	0.04	0.0	0.1

Considering all types of operations, the uplink and downlink data rates, including technical acknowledgements, for Route Data Delivery service are:

Uplink Rate = 0.9 messages/second
Downlink Rate = 1.0 messages/second

If added to the other RNAV data link messages, overall uplink rate becomes 15.4 messages per second, and downlink rate becomes 25.9 messages per second.

(Reference 7)

Table 3-3

SUMMARY OF TACTICAL UPLINK MESSAGE RATES
FOR IFR ARRIVALS AND DEPARTURES IN A TCA

Message type	Number of messages/aircraft		number of minutes under control	number of messages per aircraft per minute	
	arrival	departure		arrivals	departures
Altitude Assignment	4	2	20	.20	.10
Heading Assignment	6	2	20	.30	.10
Speed Assignment	4	2	20	.20	.10
Voice Frequency Assignment	2	2	20	.10	.10
Altimeter Setting Assignment	1	1	20	.05	.05
Assigned Runway & Route Clearances	1	1	20	.05	.05
Ground Control	3	4	20	.15	.20
Enter Hold	.25	—	20	.02	—
Leave Hold	.25	—	20	.02	—
Total				1.09	.70

(Reference 7)

Table 3-4

TACTICAL UPLINK MESSAGE RATE FOR IFR ENROUTE ABOVE 10,000 FEET

	Arrivals	Departures	Overs	Withins
Altitude Assignment	3.9*	1.5*	.8*	3.1*
Heading Assignment	3.0	3.0	——	6.0
Speed Assignment	.8*	——	——	.2*
Voice Frequency Assignment	2.5*	2.5*	3.4*	3.0*
Route Clearances	1.0	1.0	——	2.0
Route Changes	.2*	.3*	.2*	.4*
Total message/aircraft	11.4	8.3	4.4	14.7
Control Life (min)	33.1*	40.2*	59.3*	46.8*
Messages/aircraft/ minute	.34	.21	.07	.32
% of Traffic	34.9*	24.8*	16.3*	24.0*
Overall Average messages/aircraft/ minute		.24 .26		.32

* Based on peak day Chicago ARTCC December 1968

(Reference 7)

Table 3-5

TACTICAL UPLINK MESSAGE RATES FOR VFR AIRCRAFT
IN TCA AND VFR HIGHWAYS

Message Type	No. Messages/Aircraft in TCA or VFR Highway	No. Minutes under control	Average no. of messages/ aircraft/minute
Altitude Assignment	1/Flight	20	.05
Heading Assignment	2/Flight	20	.10
Speed Assignment	1/Flight	20	.05
Voice Frequency Assignment	1/Flight	20	.05
Altitudes Setting	1/Flight	20	.05
IPC Advisories	0.1/min	20	.10

Total =.40

(Reference 7)

Table 3-6

AVERAGE UPLINK MESSAGE RATE FOR 1995, PEAK TRAFFIC IN LAX BASIN

Aircraft Category	Per Aircraft Message Rate (Messages/aircraft/min)	Number of Aircraft	Average LAX Basin Message Rate (Messages/sec)
IFR arrivals	1.09	67	1.2
IFR departures	0.70	67	0.8
IFR holds	0	16	0
GA overflights	0.26	280	1.2
IFR withins	0.32	50	0.3
IPC advisories in mixed airspace	6.0	1010	100.0
IPC commands in mixed airspace	.80	1010	13.4
VFR's in TCA/ VFR highways	.40 .30 ATC .10 IPC	265	1.8 1.3 ATC .5 IPC
TOTAL ALL	———	1700	118.7 4.8 ATC 113.7 IPC

(Reference 7)

Table 3-7

DOWNLINK TACTICAL MESSAGE RATE
FOR LAX BASIN DURING PEAK TRAFFIC

Type of Downlink Message	Average Number of Messages/Sec
Technical Acknowledgement	118.7
Pilot Acknowledgements	18.2
MLS Position Report	12.0
Pilot Requests	0.4
	Total =149.3

APPENDIX B

RNAV INTERACTION WITH FSS AUTOMATION

B.1 INTRODUCTION

The Upgraded Third Generation ATC System (UG3RD) includes, as one of its nine major elements, the considerable revamping and enhancement of the flight service station system. This is referred to as the Automated FSS Program. The near term FSS improvements, many of which are designed to facilitate transition to the automated FSS environment, fall under the auspices of the FSS Modernization Program. The purpose of this portion of the study is to address the potential impact of RNAV implementation on the current, interim and automated FSS system.

B.2 FSS SYSTEM DESCRIPTION

This section presents a brief description of both the current and automated flight service station systems. The level of detail provided has been limited to that necessary for the understanding of the RNAV impact analysis. More detailed descriptions can be obtained in References 16, 17, 18 and 24. The automated FSS program plans have undergone modification significantly in certain areas recently. Reference 24 is the most recent official definition of future plans, while the other three documents give historical perspective. The FSS descriptions contained herein are based upon these documents, and upon meetings and subsequent discussions with FAA/SRDS [19], NATCOM/WMSC [20], and Atlanta FSS [21] personnel, and are believed to be current and accurate with regard to FSS concepts. Supporting documentation of the finer details of FSS operation, however, are not available. For the most part, any areas of uncertainty which are of major importance to the FSS concept have little, if any, bearing on RNAV impact.

B.2.1 FSS Functions

For purposes of reader familiarization and to provide a framework for the description of the current and future FSS systems, a listing of the basic FSS functions will be presented in this section. The functions are reasonably self-explanatory and the detailed presentation of their purpose and method of accomplishment will be deferred, as this is an integral part of the RNAV impact evaluation.

The flight service stations currently perform the following basic functions:

(1) Surface Weather Observations (airport advisories)
(2) NAVAID Monitoring (NOTAM processing)
(3) Mass Pilot Weather Briefings
(4) Individual Pilot Weather Briefings (and PIREP's)
(5) IFR/DVFR Flight Plan Processing
(6) VFR Flight Plan Processing (initiation of Search and Rescue operations
(7) Emergency Flight Assistance Service
(8) ARTCC/Pilot Backup Communication (relaying ATC/pilot messages)
(9) Law Enforcement Assistance
(10) Administering Airman Examinations

It should be noted that these functions can be grouped or categorized in a variety of ways. The scheme adopted here is intended to facilitate the subsequent discussions of RNAV impact.

B.2.2 Current System and Facilities

The current FSS system can be best characterized as an extensive network of flight service stations and communication facilities. The stations, of which there are 292, are staffed by a total of 4,000 personnel trained in the areas of weather, aviation and ATC procedures. The communication facilities enable FSS personnel to communicate with the National Weather Service, pilots (both before and during flight) and the ATC system. Within this network, the FSS gathers, disseminates and exchanges information and provides emergency assistance.

A flow diagram depicting the FSS and related communication networks is provided in Figure B.1. The major elements of the FSS system will now be explained.

Approximately half of the FSS workload involves weather dissemination. A critical element to the success of these functions is the FSS support and access of a centralized national weather data base. The FSSs support the existence of such a data base through the surface weather observations, NAVAID monitoring and pilot report (PIREP) processing functions. The synoptic weather information is disseminated via the Service C teletype system. Other aviation weather data and NOTAM information is disseminated via national weather communication. Each of these teletype systems have centralized circuits at the National Communications Center/ Weather Message Switching Center (NATCOM/WMSC) in Kansas City. Through the WMSC, the weather data can be channeled to any of a variety of subscribers. In particular, the data is made available to the National Weather Service. It is appropriate to note that about half of the basic weather observations used by the NWS for the purpose of making forecasts are provided, in this way, by the FSS system. The National Meteorological Center (NMC, Suitland, Md) is also connected to the WMSC. The NWS Weather Service Forecast Offices (WSFO) prepare a great many aviation oriented weather forecasts which, in turn, are available to the FSSs through the teletype systems.

FSS communication with the ATC system (towers, ARTCCs) is accomplished via the Service B teletype system and interphones. Regular telephone service provides backup communication when necessary.

The FSS/pilot communication capability is provided by radio broadcast and two way radio facilities. Each FSS is capable of making radio broadcasts over the audio channels of the NAVAIDs (VOR, VORTAC and NDBs) which it monitors. This is the primary means by which scheduled or continuous mass in-flight weather briefings are accomplished. Each FSS also has two-way radio capability. In most instances, the two-way radio network is supplemented by remote communication outlets (RCO), limited remote communication outlets (LRCO) and single frequency outlets (SFO). There are approximately 500 of these facilities, which are generally located so as to remedy terrain masking difficulties and, thereby provide radio communication throughout the entire FSS region.

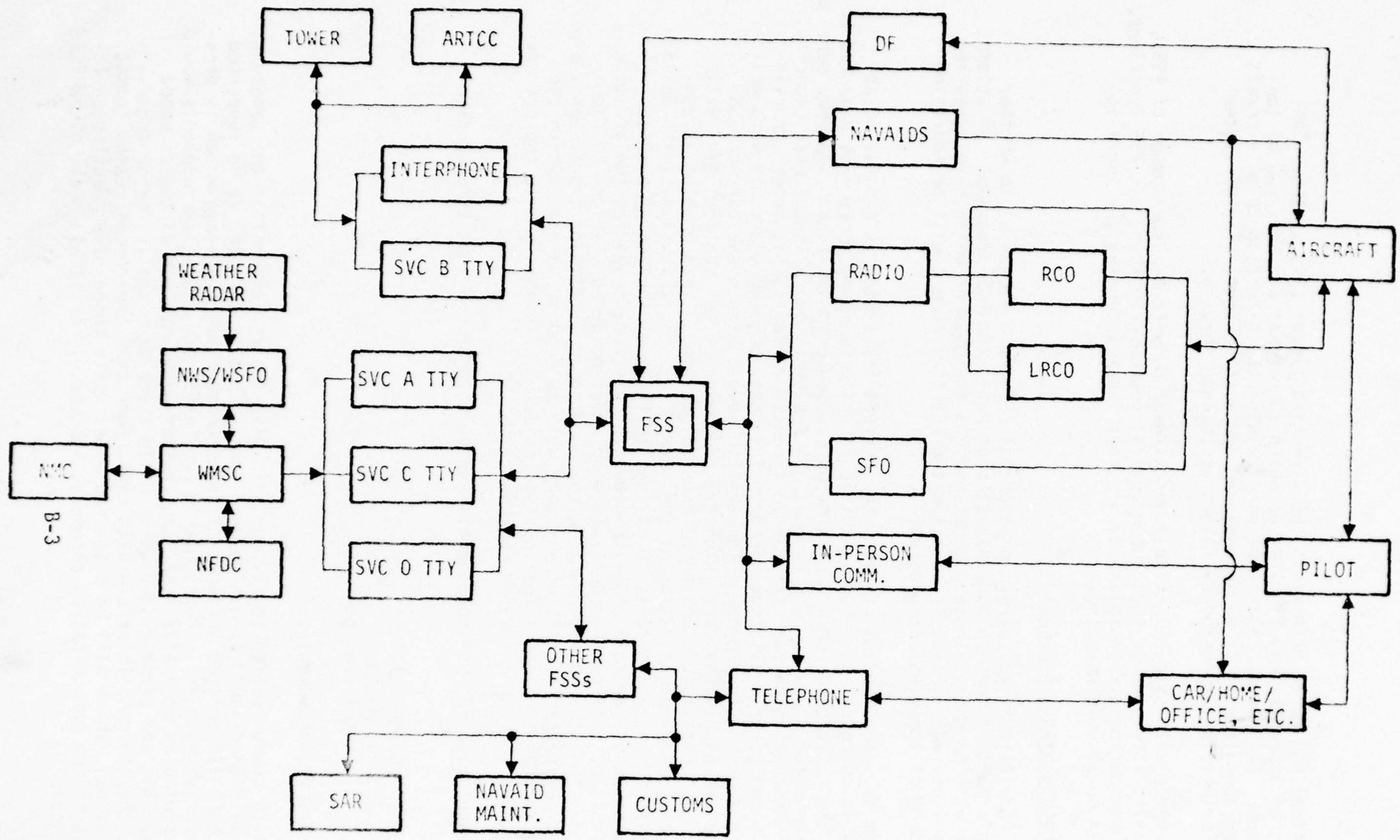


Figure B.1 Current FSS and Related Communication Networks

The final FSS radio network is the direction finder (DF) system. This consists of approximately 210 DFs, of which 70 percent are operated by the FSS system. Each DF is capable of ascertaining the direction to an aircraft providing the aircraft is radio equipped and within range. The DF system is used primarily for emergency flight assistance service.

The current FSS system is highly decentralized, with a large number of FSSs, each serving a reasonably small geographical region. Further, all FSS functions, as they are currently accomplished, are very labor intensive and there is virtually no automation support.

B.2.3 Future System Facilities

It is difficult to segregate potential FSS improvements as to whether they are a part of the FSS Modernization or Automated FSS programs. No attempt to do so will be made. Those elements of FSS improvement which have a bearing on or will ultimately lead to an automated FSS environment will be addressed independent of their parent program.

From the user's point-of-view, the current FSS system is capable of adequately discharging its responsibilities. While improved service is expected to result, the motivating force behind major FSS improvements is not improved service, but rather reduced costs. The current FSS system is operating at near capacity levels. Most aviation forecasts project considerable traffic growth, particularly in the general aviation sector. The next 15 to 20 years may very well produce a doubling (or more) of the traffic level. Since the current FSS functions are highly manpower intensive, doubling of the traffic level will essentially necessitate doubling of the FSS staffing. This problem is compounded by the decentralization of the current system, which limits the ability of the system to react quickly to changes in the distribution of traffic. Such changes cause certain FSSs to become overworked, requiring the addition of stations, but seldom can the associated under-burdened stations be decommissioned. The station network is already outdated. If major improvements are not made, additional facilities may very well be needed, in addition to the staffing increases. This situation is considered untenable and is the primary justification for the automated FSS concept.

The anticipated FSS improvements can be categorized into three general areas:

(1) Communication
(2) Automation
(3) Centralization

Communication Improvements:

The primary communication improvements involve the replacement of the teletype systems by higher speed communication lines. This is expected to be supported by the INACS (Integrated National Airspace Communication System) which is presently under development. Particularly on the FSS end, these improvements would be accompanied by more efficient input/output devices, such as higher speed printers, CRTs and graphic displays. While these programs are major undertakings, they have no interface with RNAV other than the communication format specifications, which will be discussed under their respective functions. Improvement in the communication channels, however, is critical to all other FSS improvements.

Automation Improvements:

As the program name implies, considerable improvements in the area of automation are envisioned. These are to be supported by a Central Aviation Weather Processor (AWP), and by computational facilities at each FSS. The major areas of automation improvement will now be described.

Aviation Weather Processor

The Central Aviation Weather Processor (AWP) will provide weather data services to each FSS. It will be the link between the WMSC and each automated FSS hub computer. This will include both alphanumeric and graphic data.

Centralization

The most striking proposed alteration to the FSS system lies in the area of centralization. The original automated FSS plans called for an ultimate reduction to 30 "Hub" FSSs. Later plans included Class I and II hub facilities, which were to be used jointly by both classes of stations. More recent plans have reverted to the "Class I only" concept, with a total of 20 to 30 stations envisioned. Colocation with the ARTCCs is being investigated. The centralization of FSSs still facilitate economic improvements. Underburdened stations will be more responsive to traffic patterns and workload leveling benefits will result.

In conjunction with the Aviation Weather Processor, each hub can automatically accomplish a variety of the manual functions currently performed by FSS personnel. In particular, a hub will be able to assemble weather briefing information tailored to specific user requests (automatic route briefings, for example). In itself, this capability is a major time saving feature. Longer range enhancements include the development of voice response systems (VRS). In addition to its use in individual pilot pre-flight briefings, the VRS would permit the AWP to compile and disseminate all standard mass weather briefings without specialist assistance. This includes all NAVAID broadcasts and PATWAS service (Pilot Automatic Telephone Weather Answering Service).

As opposed to earlier plans where much automation was centralized in one location, the current automated FSS plans are providing for an increased amount of the general automation capabilities to be resident within each FSS. The Aviation Weather and NOTAM System (AWANS), now operational in Atlanta, includes a resident national weather data base and software support for the automatic extraction of airport, airport-pair and region-oriented weather information.

Pilot Self-Briefing Terminals (PSBT)

The PSBT is a CRT display with two-way channels to the nearest hub FSS facility. It has two primary functions; it is the input/output device for the automatic weather briefings, and it provides a means to file flight plans. In the earlier automated FSS plans as many as 3,500 PSBTs were envisioned. These were to be available at as many airports as possible to provide easy pilot access. The original plans assumed that the PSBTs could eliminate the need for specialist intervention in as much as 90 percent of the pre-flight briefings. This would facilitate considerable reduction (or lack of increase) in FSS staffing. This assumption, however, is highly critical to the success of the concept, so much

so that current plans are placing far less emphasis on the widespread use of PSBTs. Present plans call for usage of automated terminal facilities to assist the Flight Service Specialist, with only a limited number of remote (direct user) terminals deployed. This phase of automation is refered to as the Baseline System in Reference 24, to be completed by 1985. However, plans also exist for an Enhanced System to be initiated in 1983. This Enhanced System will provide more automated capabilities, and will include widespread usage of low cost remote (PSBT) terminals. The lowest cost terminal being studied is the "Touch-Tone" (trademark) telephone, using Automatic Voice Response for computer-to-user communications.

Aviation-Automatic Weather Observation System (AV-AWOS)

The final major area of automation improvement is the projected AV-AWOS capability. The AV-AWOS components would be located in many areas, comparable to the current FSS locations, for example, and would automatically perform the FSS surface weather observation function and input the data to the WMSC. This is a long term improvement in that advances in the state-of-the-art are required to produce economical and accurate mechanisms to measure ceiling, visibility, etc. Since RNAV and conventional weather data requirements are essentially the same, when and if this system is implemented is not of concern in this study.

B.3 RNAV IMPACT EVALUATION METHODOLOGY

At the outset, as well as during the conduct of this study, there were no major areas of RNAV impact which were immediately apparent. This is not unexpected, however, in view of the fact that the UG3RD is intended to be a coordinated package of ATC improvements. On the other hand, significant degradation of the FSS or RNAV capabilities need not result only from "major" or obvious areas of interface. A primary purpose of this study, and its associated methodology, is to insure that the specific RNAV and FSS implementation plans, which have been changed considerably since their original development, will not result in any program incompatibility.

There was one ground rule adopted in this study which has a significant impact on the study methodology and results. Specifically, the study objectives were assumed not to include an evaluation of the viability or adequacy of the proposed FSS improvements. In this regard, the only assumption made was that the quality of service provided to conventional navigation users should also be provided to RNAV users.

Since RNAV implementation is not relying on the incorporation of additional functions into the FSS system, the methodology adopted for this study involves a detailed examination of how RNAV implementation will affect those functions which the FSSs are now performing or are expected to perform. Both the current and automated FSS systems, and charted and pre-planned direct RNAV scenarios, are considered. In retrospect, however, the relative implementation timing of the two programs did not become an important factor.

RNAV impact on the FSS system may take any of three distinct forms. The first includes direct impact on the FSS system induced by difficulty in processing

RNAV user requests. The second is FSS impact caused by the necessity to provide unique or expanded capabilities in the general support of RNAV implementation. Lastly, any inability of the FSS system to provide RNAV users with a comparable level of service is indirectly attributed as an FSS impact.

The methodology for the examination of the individual FSS functions and RNAV requirements has been devised so that any potential impact of the above types will be uncovered. The methodology involves a six-step process, as described below:

(1) Delineation of the purpose of the function
(2) Examination of the current method of accomplishment
(3) Examination of the future method of accomplishment
(4) Determination of the significant parameters relating to adequate performance of the function
(5) Determination of RNAV differences and/or unique RNAV service requirements
(6) Evaluation of RNAV impact (by means of establishing whether or not RNAV differences or RNAV implementation will affect the significant function parameters).

This evaluation process has been applied to each FSS function, and the step-by-step results are presented below.

B.4 RNAV IMPACT EVALUATION

The purpose of this section is to describe the results of the RNAV impact evaluation. Each of the ten basic FSS functions are described in detail, including their purpose, current and future methods of accomplishment, significant function parameters, RNAV-peculiar requirements and finally, RNAV impact (if any). The descriptions contained herein are to some extent redundant with regard to the previous sections and intentionally redundant relative to the reference material. They are furnished in the interest of providing a self-contained analysis. Areas wherein no RNAV impact was revealed are described with the level of detail necessary to support the conclusion and to provide the reader with sufficient information to re-evaluate the conclusion if changes to current FSS plans are made.

B.4.1 Surface Weather Observations and Airport Advisory Services

Purpose of Function

More than two-thirds of the FSSs currently take hourly surface weather observations. The primary purpose of this function is to provide information to the National Weather Service. Approximately half of the basic weather observations utilized by the NWS are provided by the FSS network.

Where FSSs are located on airports without control towers, they also provide airport advisory service. This service includes providing pilots with basic airport-oriented weather data (wind, barometer, etc.), runway-in-use information and any pertinent local traffic data.

Current Method of Accomplishment

Both of these services are entirely manual exercises, conducted at the FSS site. The weather information is distributed throughout the weather data system via the Service A teletype circuit. Airport advisory information is disseminated as a part of the weather briefing activities (described later).

Future Method of Accomplishment

With an ultimate reduction to approximately 20 FSSs, it is apparent that a change in the weather data collection system is necessary. The exact plans are not definitized. The requirement for weather observations may be the limiting factor in the speed with which the FSSs can be consolidated and eliminated. It is anticipated that a reasonable quantity of small FSSs, devoted almost exclusively to weather observations, will be required throughout an interim period. These FSSs will also continue the airport advisory service as necessary. The long-term plans, however, involve the FSS discontinuance of both functions. In addition to the AV-AWOS system, the alternatives for weather observation include transferral of the function to the NWS and/or the use of private contractors (FBOs, for example). Airport advisories may also be accomplished by FBOs, but, and in contrast to the weather observation function, complete discontinuance at many non-tower airports is considered a feasible approach.

Significant Parameter

While weather data must satisfy a variety of self-evident criteria in order to be useful, there are no significant parameters which have any bearing on RNAV impact.

RNAV Difference

None

RNAV Impact

None

B.4.2 NAVAID Monitoring (include PIREP data)

The purpose of NAVAID monitoring is to maintain current knowledge of the status of the NAVAIDs. Most VORs, VORTACs, NDBs, and some ILSs are monitored by the FSSs. The complete FSS responsibility in this area includes verification of the malfunction, NOTAM issuance, notification of maintenance personnel and the activation of alternative NAVAIDs where available.

Current Method of Accomplishment

The existing NAVAIDs (VORs, VORTACs and NDBs, in particular) serve two primary functions: to support instrument navigation and to broadcast weather and NOTAM data. The facilities are monitored primarily by means of automatic monitoring circuits, incorporated into the hardware, which alert FSS personnel when a malfunction occurs. The automatic monitoring capability for a VOR generally includes receiver hardware mounted so as to receive the VOR signals as they emanate in one direction. In this manner, signal bias, strength and general noise level can be checked. Signal perturbations which affect only certain directions usually cannot be detected; however, from a hardware standpoint, this is not a common occurrence. The regional or directional unsuitability of signals generally stems

from multi-path effects (scalloping). These are usually repeatable or permanent perturbations and hence, detectable by FAA flight inspections. Pilot reports (PIREPs), however, provide the only real-time data on airborne signal suitability. The FSS reception of the audio broadcast channels of the NAVAIDs provides a back-up monitoring capability.

Future Method of Accomplishment

No major changes to the monitoring functions are envisioned in the automated environment, except that monitoring will be further remoted to the FSS hub facility.

Significant Parameter

VORTAC (or VOR/DME) facilities provide virtually all of the navigation support for RNAV operations. This is true now and will continue to be the case throughout the time frame of interest in this study. Certain more sophisticated RNAV systems are capable of processing DME (or VOR) signals from two stations; hence, independent VOR or DME facilities are also of concern. No RNAV systems utilize NDBs. The use of VLF stations or navigation satellites is not considered in this study.

The significant aspects regarding the monitoring of NAVAIDs include the signal strength, noise and bias as they exist within the entire intended region of coverage.

RNAV Difference

Regarding the use of NAVAID signals, RNAV differs from conventional navigation in a very important way. Under the assumption that the aircraft actually stay on or near their route, conventional VOR or VOR/DME systems utilize very few of the available VOR radials. RNAV routes, on the other hand which would typically not overfly the VORTAC, traverse and thereby utilize many radials.

RNAV Impact

In a charted RNAV environment, NAVAID performance will be checked and monitored in virtually the same way as today. Despite the fact that more VOR radials will be relied upon, the flight inspection or PIREP data will automatically provide the appropriate information. As RNAV routes are certified and used, however, particularly in an interim or transition period, there will be more routes with fewer flights each than is currently the case. The requirement that the automated FSSs be able to accommodate the increased number of routes (for NOTAM purposes, among others) constitutes a significant impact. More discussion in this regard will be provided in Section B.4.4.

As pre-planned direct RNAV attains greater utilization, the problem of route-oriented PIREP data will be exaggerated. Further, it will be necessary that the FSS automation capabilities be designed so that PIREP data, in addition to formal NOTAM data, can be organized relative to the geographical region, rather than route(s) affected. This is an impact in that it must be accomodated within the software systems, but no major difficulty is anticipated.

B.4.3 Mass Pre-Flight and In-Flight Weather/NOTAM Briefings

Purpose of Function

Mass pre-flight briefings are intended to provide sufficient weather information for the pilot to make a preliminary go, no-go, decision. Mass in-flight briefings provide a means for the pilot to receive reasonably current weather information as the flight progresses. When the weather is stable (predictable) and not unduly severe, the briefings satisfy virtually all of the in-flight weather requirements. Under more adverse conditions, personal attention on the part of a specialist may be needed.

Current Method of Accomplishment

The FSS specialist has access to virtually all aviation-oriented weather data via the Service A teletype and the Weather Message Switching Center including many airport, regional and route (airport-pair) oriented weather forecasts prepared by the NWS. These forecasts including regional information and, in most cases, directional information (i.e., major routes) are disseminated by the FSSs through the PATWAS service. Taped weather briefings are also broadcast over NDBs which thus serve both pre-flight and in-flight functions. In addition to the use of NDBs, in-flight briefings are broadcast over VOR stations. These include TWEBs (continuous transcribed weather broadcasts) and hourly scheduled broadcasts. Weather information is broadcast over more than 900 VORs.

Future Method of Accomplishment

From the pilot's point-of-view, the automated FSS system will provide comparable, if not identical, mass weather dissemination functions. Expanded PATWAS operation is envisioned, but the use of NDBs and VORs will remain unchanged. With regard to the FSS, there may be automation improvements to ease workload. Of prime importance is the potential creation of automatic voice response capability. This may evolve into any of several forms; however, the essence of the capability is that the FSS specialist can extract voice rather than text from his system. The content will be identical.

Significant Parameter

The purpose of mass briefings is to provide general area information, suitable for use by many pilots, hence, suitable for use on many specific routes. Whether or not the routes are RNAV is, therefore, of no consequence and there are no significant parameters relating to RNAV.

RNAV Difference

None

RNAV Impact

None

B.4.4 Individual Pre-Flight and In-Flight Briefings

Purpose of Function

Under nominal circumstances, the most important weather briefing is the final pre-flight weather briefing, the purpose of which is to facilitate the entire flight planning process (including route and altitude selection, determination of fuel requirements, etc.). In-flight briefings serve a variety of functions as dictated by the particular situations. The need for personalized in-flight briefings generally implies that unusual, adverse, or at least unexpected weather is imminent.

Current Method of Accomplishment

The FSS weather data acquisition is accomplished in the same manner as described previously. Pre-flight briefings are disseminated primarily by telephone; 10 to 15 percent are conducted in person. In the current environment, very little automation capability is available and the briefings are, therefore, highly personalized. In-flight briefings are provided via two-way radio communications. A part of this service is referred to as the Enroute Weather Advisory Service (EWAS). This consists of the use of a single frequency for all pertinent FSS or pilot weather advisories. Any pilot monitoring the frequency will obtain all relevant weather data without active solicitation.

Weather briefings are the most labor intensive activity conducted by the flight service stations. This function is the prime target for automation improvements.

Future Method of Accomplishment

Considerable research has been devoted to devising a mechanism which will facilitate pilot self-briefings. This resulted in the development of the PSBT (Pilot Self-Briefing Terminal). The user, by invoking various support programs and defining his general route of flight, could obtain detailed route oriented weather briefings and file his IFR flight plan. High levels of PSBT utilization were a key to the success of the original automated FSS plans. Certain potential problems, however, have caused reasonably major changes. The PSBT, in itself a very valuable capability, has been redefined for use primarily by the FSS personnel. An interim automated capability, currently in operation at the Atlanta FSS, involves Pilot/FSS telephone communication, as before, but specialist's utilization of what is essentially a PSBT. Briefing time, and information access in particular, is improved. This procedure may be enhanced by the use of recorders for either the pilots' or FSS's communications. For example, the specialist, after an initial conversation with the pilot, may elect to record the briefing. This can then be replayed to the pilot, as many times as needed, without further specialist intervention. Longer range enhancements involve automatic voice response systems (VRS). With this capability, the specialist would input via the CRT various route location data, but then rather than having to read the briefing off of the display, the VRS would produce a recording.

In-flight briefings will essentially be conducted in the same way as pre-flight briefings. Since the requirement for personalized in-flight briefings are somewhat less standardized, less emphasis will be placed on recordings and VRS.

As the Enhanced (long-term) System of automation improvement is implemented, remote user terminals will become more widespread. However, the information handling problems (those affected by RNAV) are the same for the cases of either remote user or hub Flight Service Specialist terminals.

Significant Parameter/RNAV Difference

Pertaining to the type or accuracy of weather information, there is no difference emanating from the use of RNAV. With regard to the FSS capabilities, the number of "routes" for which weather briefings are stored may have a bearing on the efficiency of the FSS operations, during the period of transition to RNAV.

RNAV Impact

The primary impact of RNAV stems from the existence of an increased number of available routes. This will produce no impact, however, if the route processing computer logic currently being utilized (in Atlanta) is continued. The specialist obtains the relevant weather data by means of specifying the airport-pair and a "route width". The system collects all weather reports emanating from the region defined by the great circle arc connecting the airports and the width of the band. The width is a variable and values of 25 to 50 miles are typical for routes of medium length. Logic of this type is unaffected by the actual existence of routes (charted or pre-planned). Also, the differences between RNAV and VOR routes of medium length are certainly sufficiently subtle that the suitability of the "great circle arc/route width" concept is not dependent upon the specific type of route being considered.

Alternative logic, such as the pre-storing of route data, may be more expedient and reliable. However, if this is adopted, some RNAV impact will result. Either more route storage will be required or service to conventional users would be degraded. Further, no capability to accommodate pre-planned direct RNAV routings would exist.

B.4.5 IFR/DVFR Flight Plan Processing

The FSSs currently accomplish IFR flight plan processing for most general aviation, commuter, and supplemental air carrier and military (DVFR) flights. The purpose of this function, relative to its inclusion in the FSS operations, is that the facilities whereby flight plans can be filed are expanded and direct pilot/ATC communication is buffered. The FSSs also verify flight plan content validity.

Current Method of Accomplishment

The function is performed through the same facilities and operating scenario as the individual pre-flight (and in-flight) weather briefings. Flight plans are filed by the FSS specialist based upon information received from the

pilot via telephone or in person (pre-flight filing, or based upon two-way radio communication (in-flight). "Filing" of the plans involves their communication to either an ARTCC or tower by means of teletype or interphone (if departure is imminent). As with the weather briefings, the function is labor intensive and very little automation is currently available.

Future Method of Accomplishment

Improvement of the flight plan filing procedure by means of automation is desirable, but the extent of improvement is limited by the required information exchange between the pilot and the FSS. When the PSBT concept (for use by pilots) becomes more widespread, the communication burden will be shifted to the pilot. Otherwide, the FSS specialist will have to continue to listen and make a record of the necessary flight plan data. Recording the pilot's verbal flight plan may result in time savings and may facilitate a minor amount of work load leveling (since the plans need not be processed exactly as they arrive). The use of the CRT when it becomes coupled with the ARTS and NAS automation will considerably reduce the time required for FSS/ATC communication.

Significant Parameter

The primary concern of the pilot is that the flight plan be accurately transmitted to the ARTCC. The time required to do so is of secondary importance. While accuracy is logically equally important to the FSS, the time required for all aspects of the filing procedure is critical.

RNAV Difference

The only pertinent difference between RNAV and conventional navigation is the manner in which the route is geographically described.

RNAV Impact

The phraseology used to describe charted RNAV routes corresponds perfectly to that used for conventional routes. A route identifier is used to represent a series of route segments. Route intersections and reporting points are given names. The conventional use of a VOR or VORTAC name to depict a segment endpoint is analogous to the use of a charted and named RNAV waypoint. A previous FAA [22] study to determine the impact of charted RNAV routes on ARTS and NAS automation has concluded that the RNAV and conventional route formats are sufficiently similar that no impact on the flight plan data processors will occur. They did conclude, however, that the additional number of routes would cause a noticeable impact. However, this impact will disappear as RNAV implementation is completed. The first conclusion, pertaining to flight plan format applies also to the FSSs (i.e., no RNAV impact will result). Whether or not the quantity of routes will produce an impact will, logically, depend upon whether or not it is necessary to store the routes within the FSS facilities. Flight Plan verification cannot be fully accomplished without access to stored route data. This is necessary in order to check "spelling" and route continuity. It is anticipated that the upgraded ATC automation will include an appropriate computer verification capability. If this capability can be accessed by the FSS or be used to eliminate this portion of the FSS function, there will be no impact. Otherwise, additional FSS computer storage will be needed. Manual verification of the route descriptions is not viable, since it defeats the purpose of the automation.

With regard to RNAV pre-planned direct, several uncertainties exist. The advantage of pre-planned direct flight is that more flexibility is available in the selection or construction of routes. In order that this benefit be realized, the number of waypoints potentially available must be adequate. The current trend [25] is toward the use of charted RNAV waypoints with dual designators (labels). One designator would convey the waypoint location in terms of latitude and longitude or radial and distance relative to a specified VORTAC. The other designator would be a pronounceable five letter name. This concept is consistent with what is being done today. In order to define an IFR route, the pilot would need to convey to the FSS specialist only a list of pronounceable waypoint names. If this approach is adopted, the impact on the FSS system will be very similar to that of charted RNAV.

However, the number of waypoints required to provide adequate support of pre-planned direct flight has not been established. It is logical that as the number of waypoints is increased, their pronounceability will be degraded. It is not impossible that the concept of pronounceable waypoints may be dismissed altogether. If this occurs, waypoint designators may take the form of a random composite of digits, letters or a combination thereof. Communication between the pilot and the flight service specialist during the initial flight plan filing process would be more difficult, time consuming and prone to error. The PSBT concept would have immensely increased value under these circumstances and would virtually eliminate the impact as far as FSS is concerned. In addition, the impact would be partially offset, particularly in short to medium distance flights, by the use of routes which are, in fact, direct and, therefore, require only a minimum number of waypoints.

B.4.6 VFR Flight Plan Processing (Initiation of Search and Rescue Missions)

Purpose of Function

The primary purpose of VFR flight plans is to provide a record of aircraft destination, estimated time of arrival and general route description. This expedites both the initiation and conduct of search and rescue missions in the event that they become necessary.

Current Method of Accomplishment

VFR flight plans are constructed by the FSS in the same way as are IFR plans and involve the same flight plan data. In contrast to IFR plans, it is the responsibility of the pilot to activate the plan by means of communicating the actual departure time to the FSS. This is done by two-way radio after take-off. The FSS will then transmit (usually by teletype) the flight plan to the FSS nearest the pilot's destination. It will then be held in suspense until the pilot calls in to close the plan. If this is not done within a prescribed time period after the ETA, the FSS will actively attempt to locate the pilot via radio communication. If not located, the FSS will notify the Coast Guard, Air Force, and other appropriate organizations to initiate search and rescue operations.

Future Method of Accomplishment

Construction of the flight plan will be accomplished in the same way as for IFR plans. Transmission of the plan will be facilitated by the use of the CRT and high-speed inter-FSS communication channels. Since far fewer FSSs will ultimately exist, less inter-FSS communication will be necessary.

Significant Parameter

As with IFR plans, accuracy and processing time are of first order importance. In fact, the processing time was the primary motivating force behind earlier plans to eliminate the function altogether.

RNAV Difference

The only differences caused by RNAV implementation and/or use are the specific routes utilized and the route description formats.

RNAV Impact

The description of a VFR route is a less formal procedure, dictated by the variety of actual navigation techniques which may be used. The format used need only be manually interpretable; no automated verification is needed. Predominant use of "RNAV direct" routes is anticipated and these would be the easiest flight plans to process. The filing of charted RNAV routes will, as with IFR plans, have no impact. There is no reason to suspect that the RNAV VFR flights will be any more difficult to describe than any other VFR flight.

B.4.7 Emergency Flight Assistance Service

Purpose of Function

The primary purpose of emergency flight assistance service is to provide aid to distressed VFR aircraft. The service is also applicable, however, to IFR aircraft, particularly when there is a loss of ARTCC or tower radar contract.

Current Method of Accomplishment/Future Method of Accomplishment

Emergency assistance is logically a non-standard operation and will always involve the personal attention of one or more flight service specialists. The facilities to be utilized in the automated FSS environment are essentially the same as those used today. These include two-way radio communication equipment and a network of direction finders. Remote communication outlets are currently in use to extend the radio range of the FSSs. In the automated environment, the reduction in the number of FSSs will dictate far more extensive use of the remote outlets; however, the mode of operation will be the same.

Emergency assistance involves three basic activities:

(1) Determining the aircraft location
(2) Providing navigational guidance
(3) Re-orienting the pilot

Depending upon the particular situation, performance of all three functions may or may not be necessary. The level of effort in each area may also vary. The only accurate explanation of how the functions are performed is simply that all available information and capabilities are utilized.

Assuming that the pilot is not certain of his position, efforts to establish his position may include any of the following:

(1) Pilot's sighting of distinctive landmarks
(2) ADF, VOR or DME readings made by the pilot
(3) One or more direction finder responses

Navigation assistance can be provided in any manner consistent with the pilot and aircraft capabilities. The possibilities vary from the prescription of headings to the construction of a new instrument-navigable route. Re-orienting the pilot, when necessary, is usually accomplished as a part of satisfactory performance of the location and guidance activities.

Significant Parameter

Logically, a variety of factors affect whether or not emergency service will be successful. Only one factor, however, bears any relevance to the RNAV discussion. Specifically, this is the extent to which the specialist is able to utilize the capabilities of the pilot and his avionics to facilitate the location, guidance and orientation activities.

RNAV Difference

Logically, RNAV-peculiar requirements result only if the distressed aircraft is RNAV equipped and the avionics are operational. Further, the RNAV equipment can be utilized, if necessary, in a manner similar to conventional navigation. However, RNAV provides increased navigational capabilities. Under appropriate circumstances, it may be possible that RNAV could be used to fly an independently navigable course (i.e., to avoid weather or terrain, for example) when such would not be possible for conventional navigation. Also, the ability of RNAV to facilitate approaches to uninstrumented runways, or to locate a nearby airport during poor visibility, can very conceivably have a considerable beneficial impact in a critical situation.

RNAV Impact

There is no RNAV impact that stems from unique RNAV requirements. Further, one can expect that in the vast majority of instances wherein emergency assistance is provided, the existence of RNAV equipment will be inconsequential. It is possible, however, that circumstances will arise when the unique RNAV capabilities can be utilized to more greatly enhance safety than can conventional navigation. In these situations, it is assumed that the FSS system will incur a responsibility (and hence impact) for being fully familiar with RNAV operations.

B.4.8 Relaying ATC Information and ARTCC/Pilot Back-up Communications

Purpose of Function

The current FSS network includes a radio communication system which is more encompassing than that of the centers and towers. The FSS system is, therefore, used, when necessary and possible, to supplement (expand) the center/tower information. It also serves as a back-up communication capability.

Current Method of Accomplishment

The flight service stations can communicate with the ARTCCs and towers via interphone, regular telephone and teletype. FSS/pilot communication is accomplished primarily by the two-way radio network. The network is extensive and includes, in addition to facilities at approximately 300 FSSs a variety of remote communication outlets (RCOs). The RCOs are generally located in such a manner as to provide reasonably comprehensive low altitude coverage.

Future Method of Accomplishment

The automated FSS environment will include the same basic communication capabilities. Far more extensive use of RCOs is envisioned, but this will be functionally identical to the replacement of FSSs by a remote capability. The potential "joint use" (ARTCC/FSS collocation) concept will, logically, enhance ARTCC/FSS communication.

Significant Parameter

The success of the communications function is dependent upon the time required for, and accuracy of, the transmissions.

RNAV Difference

The only difference in the communications required by the use of RNAV stems from the occasional use of different phraseology.

RNAV Impact

In related studies [15], RNAV has been shown to produce controller (both terminal and enroute) communication time benefits. The phraseological differences will, therefore, not adversely impact the FSS. The only FSS impact is the requirement for RNAV familiarity. The use of pre-planned direct RNAV will have no compounding effect.

B.4.9 Airman Examinations

Purpose of Function

The purpose of FSS administration of airman examinations is to expand the locations at which such tests may be taken.

Method of Accomplishment

The FSSs accomplish this function simply by the provision of space and exam monitoring. In an automated environment, this function will be discontinued since the advantage of widespread facilities will disappear.

RNAV Impact

Currently, there is no separate RNAV examination, and hence, no RNAV impact.

B.4.10 Law Enforcement Assistance and Customs Service Support

These functions are performed as an assistance service to the law and customs agencies. There is no RNAV interface and no direct RNAV impact. In view of the fact that no RNAV impact has been identified which will adversely affect FSS capacity or staffing requirements, the capability of the FSS to provide this assistance should be unaltered by the implementation of RNAV.

B.5 SUMMARY AND CONCLUSIONS

As was previously mentioned, the impact of RNAV implementation on the FSS system could have taken any of three forms. These include an increased difficulty in handling individual RNAV user requests, increased burden associated with the general support of RNAV operations or an inability to provide comparable service to RNAV users. Based upon the analysis of the previous section, processing of RNAV requests will be more difficult or more time consuming only under certain potential RNAV pre-planned direct implementation scenarios. Moderate, but not unforeseen, impact will result from RNAV data base support requirements in the interim transition environment. No area was found wherein the FSS system will be unable to provide comparable support to RNAV users. In this regard, however, there is an exception of a somewhat extraneous nature which will be addressed as a separate entity in Section B.6.

The primary areas of RNAV impact are summarized as follows:

(1) Increased difficulty in handling pre-planned direct flight plans:

The potential benefits of RNAV pre-planned direct flight stem from the increased number of "waypoints" which will be made available for the purpose of constructing routes. The exact manner in which the waypoints will be named or otherwise designated has not been established. There will be essentially no RNAV impact on the FSS system if pronounceable waypoint designators are utilized. If this is not the case, however, FSS/pilot communication time may be significantly impacted. Development of the supportive data for the quantification of this impact was not within the scope of this study.

(2) Data base support requirements:

During the RNAV implementation period, an increased number of routes will exist. There are a variety of FSS functions which require access to the geographical descriptions of the routes. These include flight plan verification and NOTAM/PIREP processing. The impact on the FSS system stems from the requirements for additional computer storage. This impact is not considered to be of consequence if properly planned for. In a pre-planned direct environment, the computer impact will be greater while high altitude charted routes are maintained, and considerably less, if and when, the routes are deleted.

(3) FSS training:

The fact that the FSS specialists must be familiar with RNAV operations is an obvious RNAV impact. The basic RNAV capabilities, however, are not complex and extensive formal training should not be required.

In summary, there are no areas of RNAV impact which pose any major difficulty in the design or operation of the automated FSS system. There are several factors however, which must be considered. Of primary importance is that communication time must be viewed as a critical factor in the development of pre-planned direct implementation plans, and that adequate core storage should be available in the FSS system design for handling the increased number of routes during the transition to RNAV.

B.6 FLIGHT PLANNING CAPABILITIES WITHIN FSS SYSTEM

The study methodology applied in the previous sections involved analyses of the functions or services which the FSS system is currently performing or is expected to perform. Since the current RNAV implementation plans are not relying on the activation of additional FSS functions, all areas of potential direct RNAV impact can be identified in this manner. However, based upon the RNAV implementation plans as they now exist, there are several areas wherein RNAV pre-planned direct users will not receive service comparable to that of charted-route RNAV users. In general terms, the difference in the service stems from the obvious fact that they may not receive the information which is normally made available on a chart. Whether or not this information will be provided, how and by whom, are all undecided issues at this time. As such, there is no proper way to assert that an RNAV impact will result.

With the use of automation, however, certain pertinent "flight planning" services could be provided and these would greatly enhance pre-planned direct capabilities. Further, there are several reasons why the performance of this function would be best accomplished within the FSS system. A discussion of this issue within the context of RNAV/FSS interface is, therefore, considered appropriate.

The use of pre-planned routings will necessitate a variety of procedural and operational changes. Of greatest importance is the fact that the ATC system will be granting IFR clearances for routes which, at least conceivably, have never been flown. The impact of this situation can be best brought into perspective by listing several of the basic pieces of information which generally appear on or are implied by an airway chart. These include:

(1) Minimum enroute altitude (MEA)
(2) Minimum obstruction clearance altitude (MOCA)
(3) Minimum reception altitude (MRA)
(4) Minimum crossing altitude (MCA)
(5) VORTAC selection and changeover points
(6) Waypoint location
(7) Adequacy of signal coverage (strength and accuracy)
(8) Restricted area avoidance

Associated with each of the above is an FAA activity, such as topographical analysis and flight checking, which emanates from an FAA responsibility to insure an adequate level of safety. The FAA is capable of accommodating these responsibilities due to the fact that the number of routes is finite (albeit large) and the results can be disseminated to the users (via charts).

In a pre-planned direct environment, a different approach must be adopted. One alternative involves the design of general purpose charts which would allow the pilot to perform all of the previously mentioned functions. This would be analogous to the pilot's utilization of standard VFR charts, with an additional requirement to obtain detailed VORTAC coverage information. While this approach is viable, it would lead to non-standard station and waypoint procedures and would be conducive to blunders. The FAA provision of a real-time computerized service to accomplish these functions may be a feasible and beneficial alternative.

There are essentially only two FAA organizations which could accomplish these tasks, the Air Traffic Service and the FSSs. Incorporation of the function within the FSS system is consistent with the operational concept that the FSSs provide information exchange and other flight planning assistance (i.e., weather and NOTAM services), while the ATC provides operational support for airborne aircraft. Within the strict context of this study, this will impact the FSS system only if the decision is made that the FSSs will assume this responsibility. An auxiliary conclusion of this study, however, is that this alternative has sufficient merit as to warrant further investigation.

APPENDIX C

RNAV INTERACTION WITH UPGRADED ATC AUTOMATION

C.1 METERING AND SPACING PERFORMANCE IMPACT OF RNAV

C.1.1 Introduction

Techniques for performing the Metering & Spacing (M&S) function have been under development for the past several years as a part of the Upgraded ATC Automation program of the UG3RD. The basic function of an M&S system is to consider arriving aircraft and requested departures, schedule landing and departure time slots for each aircraft, meter arrival aircraft into the terminal airspace at the appropriate rate, sequence the aircraft so as to achieve the predetermined arrival/departure time slots, and space the arrivals accurately in order to minimize interarrival spacing. The primary objective of M&S is to increase runway capacity (and therefore reduce delays) by means of preventing unproductive time gaps between arrivals/departures through scheduling, and by means of closely controlling interarrival and departure-arrival spacing. The ability of an M&S system to perform the scheduling function is dependent primarily upon the sophistication of the control logic developed and implemented in the system. The ability to control interarrival spacing, however, is dependent upon other systems parameters such as surveillance accuracy, pilot/controller response time variability, aircraft control accuracy and wind forecast errors. As advanced control techniques are implemented (RNAV and 4D time control), they will in turn affect interarrival spacing control accuracy. The relative performance of Metering and Spacing systems based upon radar vector techniques, RNAV techniques, or 4D time control techniques is the central subject of this section.

The primary motivation behind the implementation of M&S systems is to increase airport capacity without requiring new runway construction, and independent of new aircraft landing systems, guidance techniques, surveillance systems or wake vortex avoidance systems. Even as other systems are developed which improve airport capacity, M&S capabilities will still be required to take full advantage of the available runway capacity potential of these other systems.

Metering and Spacing is accomplished through control of final approach gate arrival time using path stretching and speed control techniques (primarily the former). The aircraft arrival sequencing area is divided into two or more control areas where path length modification radar vectoring is applied. The initial area(s) are designed to provide a large degree of time controllability (three to five minutes maximum delay) through path stretching. This wide latitude of control is necessary in order to accomplish initial aircraft sequencing and to compensate for terminal arrival time randomness, or to compensate for holding pattern departure time randomness. The controllability of the subsequent control area(s) is much narrower, since they are primarily intended for correction of delivery time errors which accummulate in the earlier control areas, and for accommodating minor updates to the gate arrival time schedule.

Early metering and spacing techniques were developed by Computer Systems Engineering under contract to the FAA, the results of which were reported in Reference 29 and numerous subsequent reports. The M&S geometry developed by CSE consisted basically of two time control areas (for gross and fine control), plus a final approach intercept vector to provide a final adjustment to gate

arrival time. These techniques have been subsequently refined by FAA, MITRE and others to result in a proposed set of M&S techniques which provide several improvements over the earlier techniques. For example, the amount of airspace involved is reduced and the severity of the turns required is reduced. These techniques have been applied to produce a specific M&S design for the Denver Terminal area (see Reference 30), which will form the basis for M&S simulation tests to be conducted in the near future.

The Denver M&S design of Reference 30 was specifically chosen as the basis of the study of RNAV integration, and of 4D RNAV integration, since it is currently under serious consideration for testing and eventual implementation. Therefore, it was considered to be advisable to demonstrate the ability of RNAV (& 4D) to operate within that framework such that RNAV operations could be introduced in a compatible, evolutionary manner. This is not meant to imply that the design studied is necessarily the optimum technique which could be developed under the assumption of an all-RNAV (or 4D) environment. Improvements in terms of controllability, delivery accuracy or workload might be achievable if such an approach were taken. However, such studies were not considered to be within the scope of this task since it is concerned with RNAV integration within the UG3RD system as it is presently defined, not as it might be defined if a different set of ground rules were adopted.

The M&S technique developed for Denver is illustrated in Figure C.1, which was taken from Reference 30. As traffic approaches point A for North traffic, or point A' for South and West traffic, they are assigned a firm schedule time in the sequence of arrival aircraft. Traffic from the East arrival along an extension of the approach course and are generally assigned arrival slots with priority over other traffic since the degree of controllability along the Byers route is much less than that for the other arrival routes. While radar vectoring may be applied to delay arrival to points A or A' when extra long delays are needed, the spacing function would ordinarily commence upon crossing points A or A'. As an aircraft approaches A (or A'), the M&S system supplies an outbound heading and speed value to the controller, based upon the amount of delay required, which he then communicates to the flight crew. This heading is derived by first computing gate (point G in the figure) arrival time based upon the nominal route length (the nominal route is shown as the solid line connecting points A, C, D, P_1 and G). Gate arrival time is then adjusted by selecting either a longer or shorter route to achieve scheduled gate arrival time. From point A, the largest delay would result from the more northerly route to point B, whereas the smallest would result from heading directly to point P (this would only be done where an excessively large time gap in front of the aircraft exists). Normally, the departure heading would be in some direction other than towards point P. As the aircraft departs point A at the requested heading, the M&S system periodically performs another computation in order to schedule the next turn. From the gate arrival time schedule, a nominal time for arrival at point P is computed. Periodically thereafter, the arrival time error at point P given that the aircraft immediately turned directly towards that point from present position is computed. This value is called the direct course error (DICE). It is monitored by the system and, as it approaches zero, the aircraft is instructed to turn direct to point P (hence it would arrive at point P on schedule). The flight is then allowed to progress until it intercepts a circle (called the P-arc) of fixed radius about point P_1, at which time the aircraft is instructed to turn to intercept the approach course. The heading requested is computed to result in a zero gate arrival time error. Normally the aircraft intercepts the localizer course autonomously. However, if "fine tuning" is deemed required by M&S, last minute localizer course intercept vectors and speed control

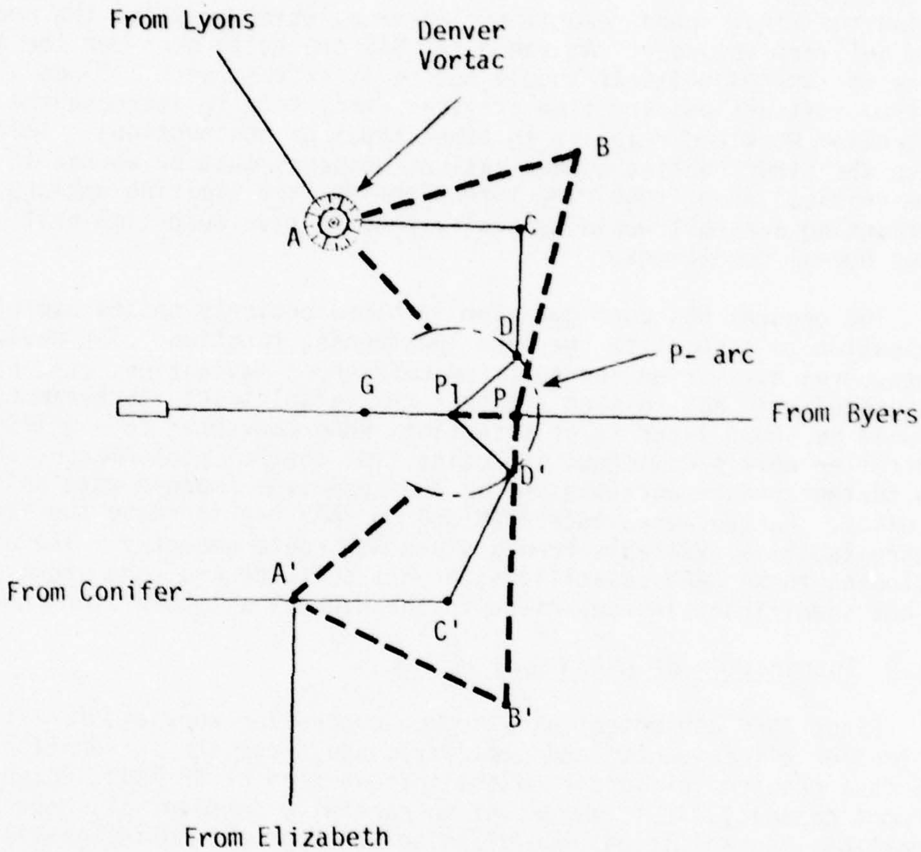


Figure C.1 M&S Geometry Used in Reference 30

instructions may be issued. Speed control is achieved by selecting the point (prior to gate arrival) where the reduction to approach speed is allowed; e.g. a late speed reduction advances gate arrival time, and vice versa.

In the M&S procedure, initial (gross) time control is achieved in the departure from Point A and the turn towards Point P, while fine control is obtained from the turn at the P-arc to intercept the final approach course, and from speed control. It is readily apparent that the successful attainment of time control accuracy is dependent upon the controller's performance in issuing the heading/speed clearances in a timely manner. The controller would be cued

in the following manner, according to Reference 30. As the value for direct course error to P gets small (20 sec.) it is displayed such that the controller may track it and time his clearance instructions accordingly. The cue for the next turn is the approach of the aircraft to the P-arc, at which time the controller delivers the indicated computed heading command. As the approach course is neared, DICE is again displayed so that a final localizer intercept vector may be issued if needed. Likewise, the DICE indication is used for timing the final speed reduction clearance, which provides the needed gate time delivery accuracy. At the gate, M&S ceases to consider the aircraft since the approach itself should not be interfered with. Since all of these control instructions are time critical, they tend to increase the level of controller workload relative to other types of instructions. This results since the other routine communications messages must be worked in around the time-critical ones, requiring more planning, and limiting options. Each approaching aircraft would typically require five such time-critical instructions under normal conditions.

The present M&S configuration is based entirely on the use of radar vector navigation to accomplish the path lengthening function. The navigation improvements, Area Navigation and 4D (time-reference) navigation, can, however, be integrated with M&S in such a manner that significant improvements will result. As will be shown later in this section, RNAV can serve to significantly decrease controller workload without impacting time control performance, while 4D RNAV can further reduce workload and at the same time improve gate arrival time control accuracy. Furthermore, both RNAV and 4D RNAV can increase the amount of time controllability available from a given M&S route geometry. The effect of including these RNAV capabilities on M&S software and core storage requirements is not significant in comparison to the overall allotment for the M&S function.

C.1.2 Integration of RNAV Capabilities

Since RNAV can potentially reduce controller workload (and therfore improve controller effectiveness and capacity), and since the integration of RNAV with M&S is a required precursor to the introduction of 4D RNAV, which can increase airport capacity, it is important to carefully consider all aspects of RNAV operational capabilities when planning the approach to integration of RNAV with M&S. Several ground rules should be observed to insure the effectiveness of RNAV as an M&S tool. First, the basic routes and M&S geometry which form the basic M&S system should be in common with RNAV routings; i.e. the same delay areas should be used so that additional airspace is not required, and the same basic routings should be used so that the RNAV traffic interacts smoothly with conventional traffic, and to simplify controller procedures and video map content. Second, the RNAV M&S design should result in control capability (controllability and delivery accuracy) which is essentially equivalent to that available with basic M&S. Third, the RNAV procedures employed should be operationally convenient to both the flight crew and the controller. Fourth, in order to fulfill the promise of reduced controller workload, it should not be necessary for the controller to be routinely required to transmit extensive data (waypoint coordinates, etc.) in order for RNAV to integrate properly with M&S. These latter two points arise due to the functional capabilities of RNAV and of differing RNAV systems. RNAV, of course, provides the capability to fly directly to arbitrary points, and so controllers could perform the M&S function by communicating waypoint coordinates for each leg. This would impose a heavy workload burden upon pilots and controllers and greatly increase blunder potential,

and so would be unacceptable. Also, system capabilities differ. Simple RNAV systems, by their nature, allow flight TO or FROM a waypoint. Therefore, the radar vector mode of M&S could be virtually duplicated ("depart Point A at XXX bearing; direct to Point P at YYY bearing; direct to Point P_1; direct to Point G; reduce speed to ZZZ knots"). However, airline grade systems do not generally have this capability, nor is it advisable to further complicate system operation by adding it. Therefore, alternative means of defining the paths must be developed.

A candidate RNAV M&S plan for route geometry and procedures has been developed which fulfills the requirements outlined above. This plan is illustrated in Figure C.2, which should be compared with the earlier figure illustrating the radar vector M&S geometry. The two relate very closely, as is evident in the following (only the northerly arrival route is discussed; the South/West route is functionally identical): As stated earlier, initial control delay may be exercised during the arrival to Point A by radar vectoring away (to the West) from the path to A, and then turning towards A at the appropriate time. While this maneuver is not to be applied routinely, it is easily duplicated using RNAV by issuing a "parallel offset" instruction followed by a "cancel offset" or "direct-to-A" instruction. The departure from Point A to the East involves the routine delay leg which is an integral element of the M&S technique. Using radar vectors (with heading given in 5° increments) any departure bearing from approximately 60° to 120° (magnetic) may be issued to an aircraft depending upon the amount of delay anticipated to be required. Then, as the aircraft proceeds along that bearing, the direct course error (DICE) in arrival time to Point P is computed periodically in order to determine the point at which the aircraft should be vectored directly towards point P to meet scheduled arrival time. To duplicate the departure from A using RNAV would be very difficult with airline type systems, since they cannot depart "from" a waypoint at a specified bearing. A solution would be for ATC to transmit coordinates of an objective waypoint to the aircraft prior to its arrival at Point A. This, however, would cause the communications and workload problems mentioned above, and so is not acceptable.

Upon further examination of the geometry involved, it was found that the degree of delay introduced by this procedure is influenced primarily by the choice of inbound bearing to Point P, not the outbound bearing from Point A. The outbound bearing affects somewhat the limits to the amount of delay available for control by choice of inbound bearing to P. Therefore, the number of choices available for outbound bearing may be significantly reduced from the twelve available with radar vectors to three or so for use with RNAV (the choices for radar vectors may likewise be reduced to the same set). Figure C.2 illustrates an arrangement using four choices: Departure bearings of 50°, 70° 90° and direct to P (120°). The route direct to P (which is then modified direct to P_1 at the P-arc) is the normal, short route used when traffic is not at a high enough rate to require M&S operation, or when an arrival stream gap occurs. The first three choices would be accomplished by designating three objective waypoints (shown as L, M and N) to create the 50°, 70° and 90° track bearings. These would be published as a part of an RNAV M&S STAR procedure, and so would be communicated by ATC using waypoint names, not coordinates. The procedure could be executed in several ways by the flight crew, depending on RNAV system capabilities. For example, the coordinates could be entered from the STAR plate (see Figure C.3) upon receipt of the clearance to Point L, M or N. Or, all waypoints could be pre-stored in sequence as a part of the RNAV data base and then called up by using the "direct-to" function, which would be an extremely simple procedure. Once the aircraft has departed on one of these

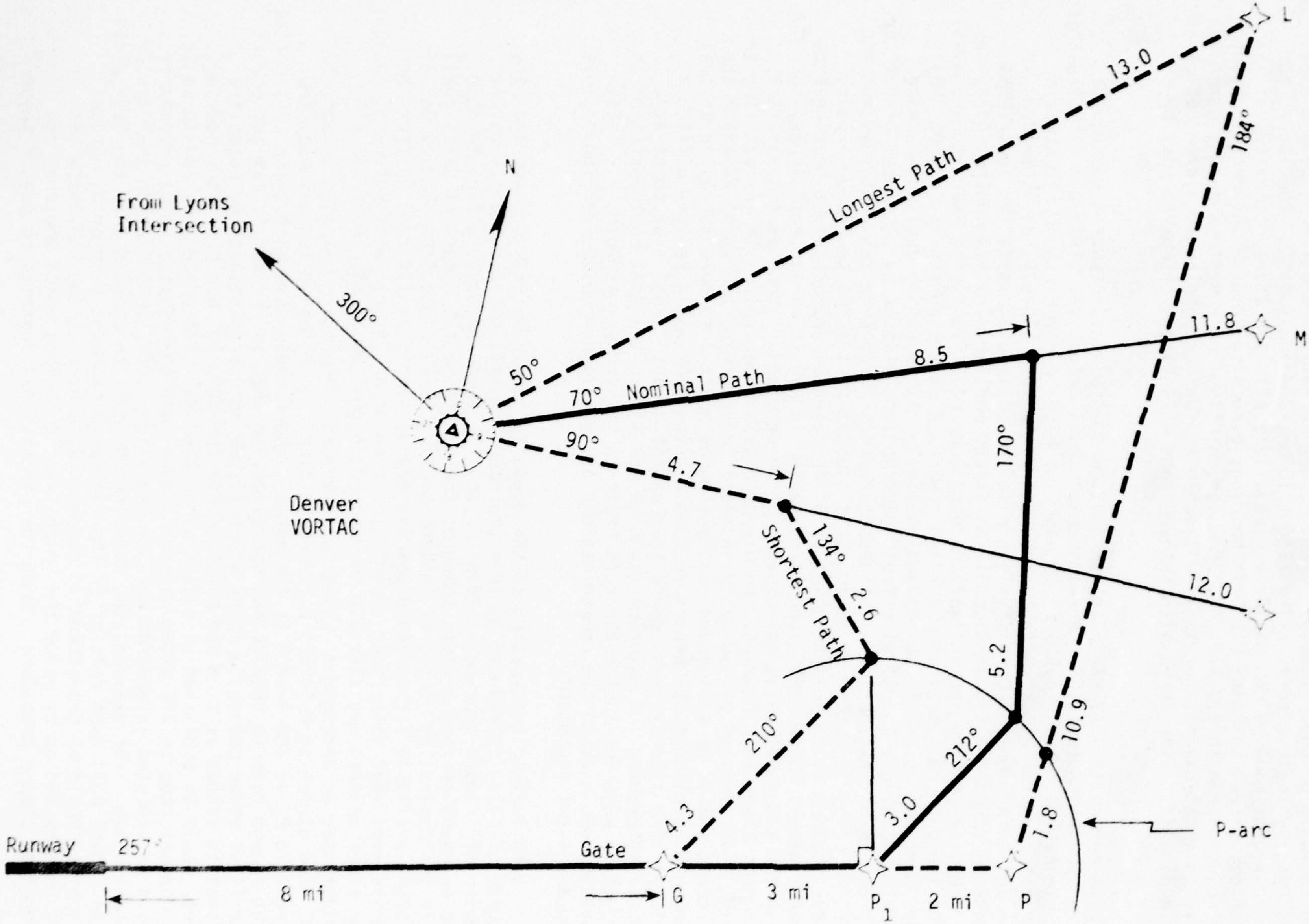


Figure C.[illegible] Candidate RNAV/Radar Vector M&S Plan

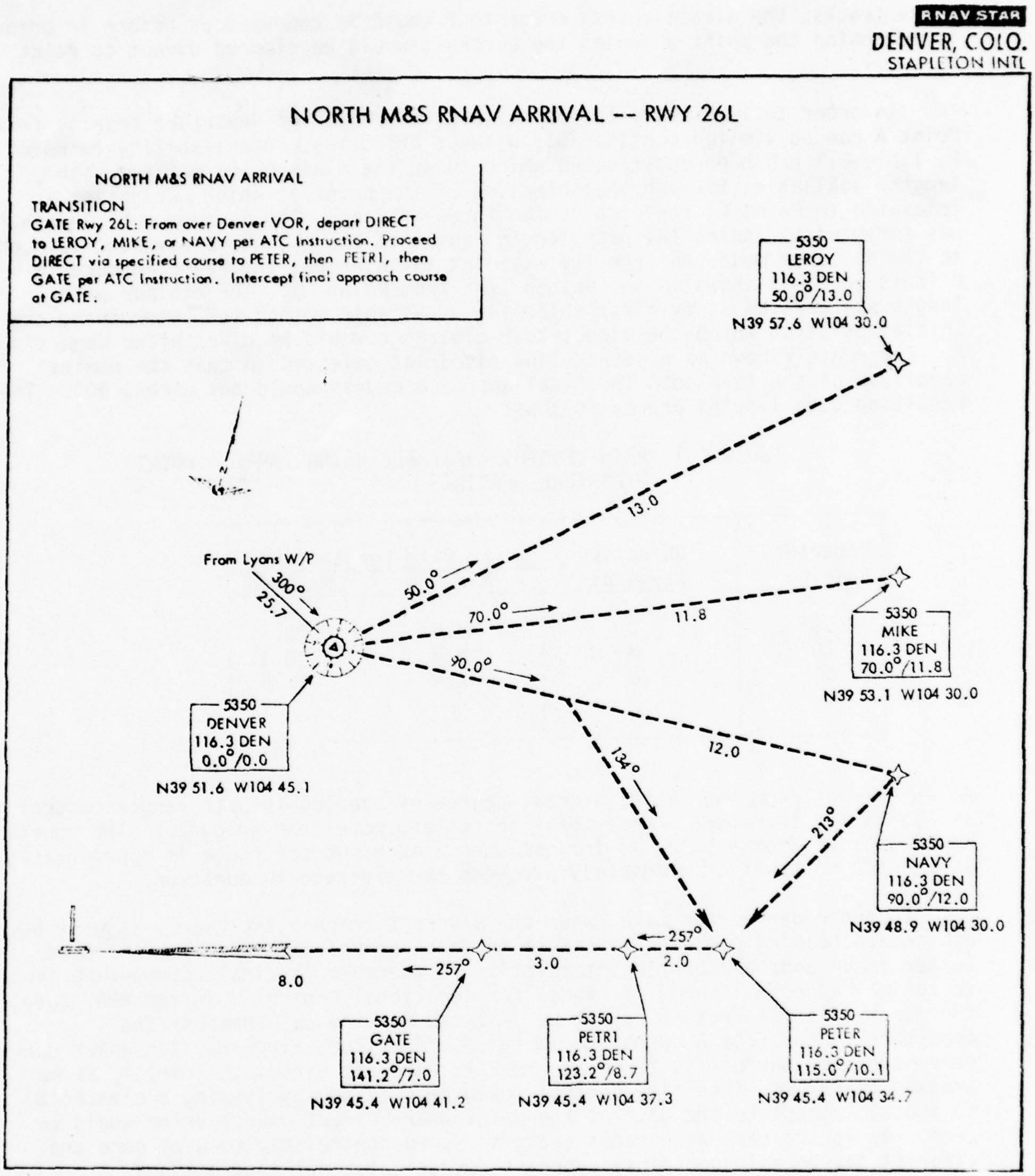


Figure C.3 Example RNAV M&S STAR Procedure

three tracks, the direct course error to P would be computed as before in order to determine the point at which the aircraft would be cleared direct to Point P.

In order to illustrate the point that the choice of departure bearing from Point A can be limited considerably without affecting controllability to Point P, Table C.1 has been constructed which shows the minimum and maximum path lengths available, through the selection of the point at which navigation is initiated to Point P, for each of the three choices. The maximum path length was computed by adding the path length from A to the objective waypoint (L,M,orN) to the distance measured from the waypoint to intercept the P-arc enroute to P (this route is shown as the dashed line from Point L). The minimum path length was arrived at by first selecting a suitable method for determining the initial point at which the direct-to-P clearance would be given after departing A. The route (shown as a dashed line also) was selected so that the nominal magnitude of the turn onto the final approach course would not exceed 90°. The resulting path lengths are as follows:

Table C.1 PATH LENGTHS AVAILABLE USING THREE A-POINT DEPARTURE BEARINGS

Departure Bearing	Objective Waypoint	Path Length (nmi)	
		Minimum	Maximum
50°	L	9.0	23.7
70°	M	8.0	18.4
90°	N	7.4	15.6

As is evident from the Table, a great degree of overlap in path length control is available; therefore, these three routes are more than adequate. The fourth route (direct from A to P) is for use when a much shorter route is appropriate; i.e., when no traffic immediately precedes the aircraft in question.

In the radar vector case, when the aircraft reaches the P-arc, it will be assigned a heading designed to result in zero arrival time error at the gate (after final approach course intercept). Furthermore, a final course-intercept vector may also be issued if needed for additional control. In the RNAV case, the first of these vectors cannot be imitated for the same reasons the departure vector from A cannot be imitated. An alternative solution which can serve the same purpose is to clear the RNAV aircraft direct to Point P_1 as he crosses the P-arc. Then time control would be obtained by issuing a clearance to proceed direct to the gate at the point where direct course error would be zero. As is the case with radar vectors, speed control may be used once the aircraft has been issued final approach course intercept instructions.

C.1.3 RNAV Contributions and Limitations

There are two primary reasons for integrating RNAV into the Metering and Spacing system. First, it has been shown that RNAV terminal area operations provide economic benefits to the airspace users, reduce controller workload, and increase airport capacity (see Section 1.3 and Reference 8). Therefore, it

is of importance to continue the implementation of RNAV as M&S procedures are introduced. The second reason is that RNAV procedures must be established in order that 4D RNAV can be introduced, which is necessary in order to achieve even better interarrival spacing control, hence greater capacity. Also, RNAV procedures can allow the use of MLS as a position reference during the final stages of arrival; this will also improve M&S performance.

RNAV should also produce some other benefits as an M&S tool for both the airspace user and ATC controller. First of all, through publication of RNAV M&S STAR procedures, the flight crew will at all times be able to remain oriented and monitor progress throughout the arrival procedure. Also, an aircraft will be able to complete its arrival and approach in an orderly manner without significant interruption to the M&S system even in event of a communications failure. In contrast, under M&S vectoring, orientation will not be as easily maintained since no position reference will be available until the localizer is intercepted. Controller workload will be reduced to a certain extent with RNAV procedures, even though the number of communications required for M&S control of each arrival does not change. The workload reduction is a result of the fact that, under radar vector M&S procedures, each of the control instructions is time-critical; i.e. each instruction must be issued precisely when the aircraft turn or speed change is required in order for the desired degree of control to be achieved. Using RNAV, however, the instructions may be issued in advance of the intended maneuver since both the objective waypoint name and inbound track bearing can be issued. The track bearing stated would thus control the point at which the turn would be initiated, rather than the timing of the message. Since most of the communications would no longer be time-critical, it is not necessary for the controller to as carefully plan the order and timing of the various routine and M&S messages which would be necessary under high traffic level conditions. It is also expected that the usage of RNAV techniques will in most cases maintain or improve the time controllability and gate delivery accuracy available with M&S using standard radar vector techniques. As is shown in the subsequent section, RNAV reduces arrival timing errors over all but the shorter legs, where errors are slightly worse. These various benefits are analyzed further in the following section.

C.1.4 Controllability and Gate Delivery Accuracy

In this section, Metering and Spacing Techniques are analyzed in order to determine the degree of time controllability available and expected gate delivery accuracies under given sets of conditions. These include basic M&S using radar vectors, M&S with RNAV procedures integrated, and M&S based on the use of 4D RNAV capabilities. Controllability and delivery accuracy have been analyzed considering the radar vector technique in Reference 30. In that analysis, which used the geometry in Figure C.1, it was determined that the time controllability available (considering jet traffic) from Point A to the gate is 232 seconds (3.9 min.) and that the resulting delivery error is on the order of 10 sec. (2σ). In that reference the RNAV case was not analyzed. Also, some aspects of the analysis technique used have been expanded or corrected in the present analysis of RNAV M&S procedures. In addition, the exact M&S geometry used in that study was not described accurately in the report. Therefore, the radar vector M&S cases have been re-analyzed along with the RNAV M&S analyses in order to produce consistent results. In all cases the geometry depicted in Figure C.2 was used.

The analysis in Reference 30 was intended to express M&S controllability and delivery error on the basis of 2σ expectations (95.44% confidence level). Controllability is the difference between the longest and shortest paths from one point to another expressed in terms of travel time. If there were no navigation and control errors, controllability is easily computed given path lengths and speeds. In the presence of such errors, controllability is diminished. Controllability may be determined to the 95.44% confidence level by using the methodology developed in the next section, which is different than that applied in Reference 30. An oversight in that reference pertaining to the computation of delivery error exists as follows; whilé error sources in the along track direction (e.g., tailwind forecast error) were considered, those in the cross track direction (e.g. crosswind forecast error) were not. Cross track errors affect both delivery error and controllability. The results of these new analyses are presented after the next section, which discusses error sources and relationships.

Error Sources

In Reference 30, the list below of 1σ values for navigation error sources is presented. These values are used in the new analysis without change except for surveillance error. This tracking error is dependent upon geometry, but is so small that a constant value (0.08 mi, 1σ) was used throughout most of the analysis for simplicity.

Table C.2 Navigation Errors (Reference 30)

One Sigma Values	
Along Track Errors:	
Airspeed Control Error	5% of IAS
Wind Forecast Error	5 knots
Radar Azimuth Error	0.25°
Radar Range Error	255 ft.
Pilot/Controller Response Variability	4 sec.
Cross Track Errors	
Heading Sensor Error	1°
Wind Drift Error	3°
Pilotage	1°

The cross track errors in Table C.2 aggregate into a net error value of 6.63° (2σ). The along track errors, except for the pilot/controller response variability (compliance error) sum to result in a net error which is a function of airspeed, distance flown after the M&S command, and position with respect to the radar site. As stated above, the position effects were disregarded through assumption of a constant surveillance error component. This allows construction of Figure C.4 which shows the speed and distance effects on 2σ error. This figure is used in the subsequent controllability and delivery error analyses.

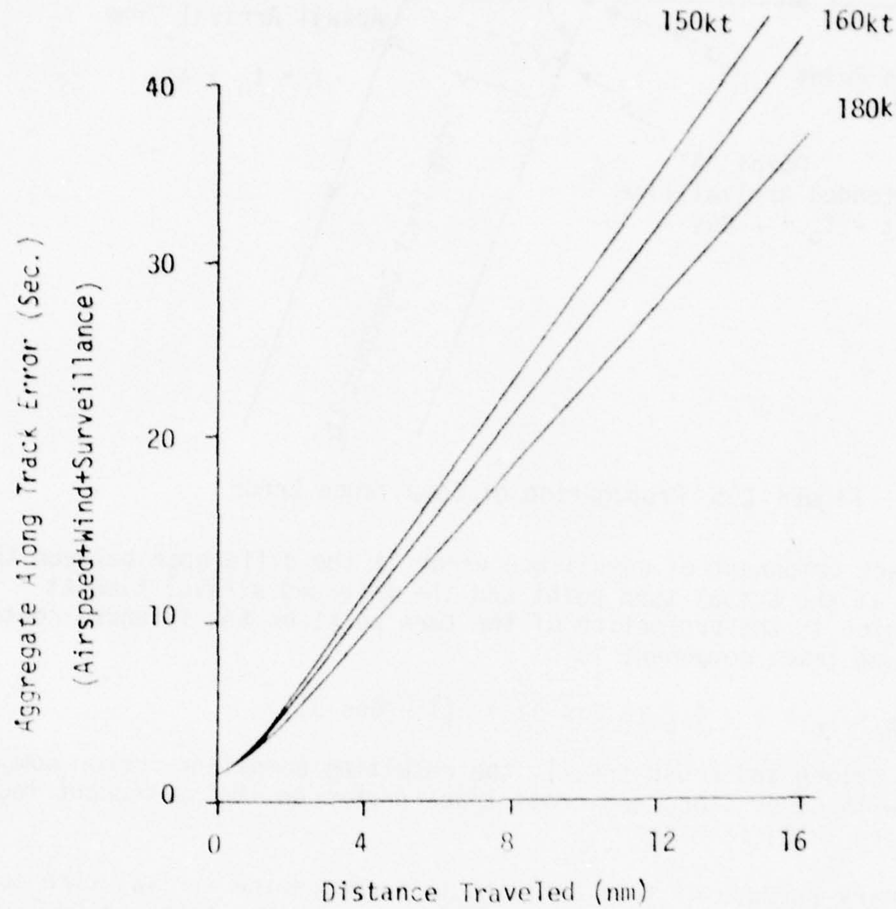


Figure C.4 Along Track Error Relationships

The pilot/controller response variability (compliance) error represents the inevitable variations in time required for the controller to initiate an M&S command and for the pilot to initiate the requested maneuver. This error can propagate into both the along track and cross track directions, depending upon the magnitude of the turn involved. In Figure C.5 the relationships are illustrated. From the figure, the cross track component of compliance error, δ, is:

$$\Delta t_c = \delta \sin \theta$$

where θ is the magnitude of the turn.

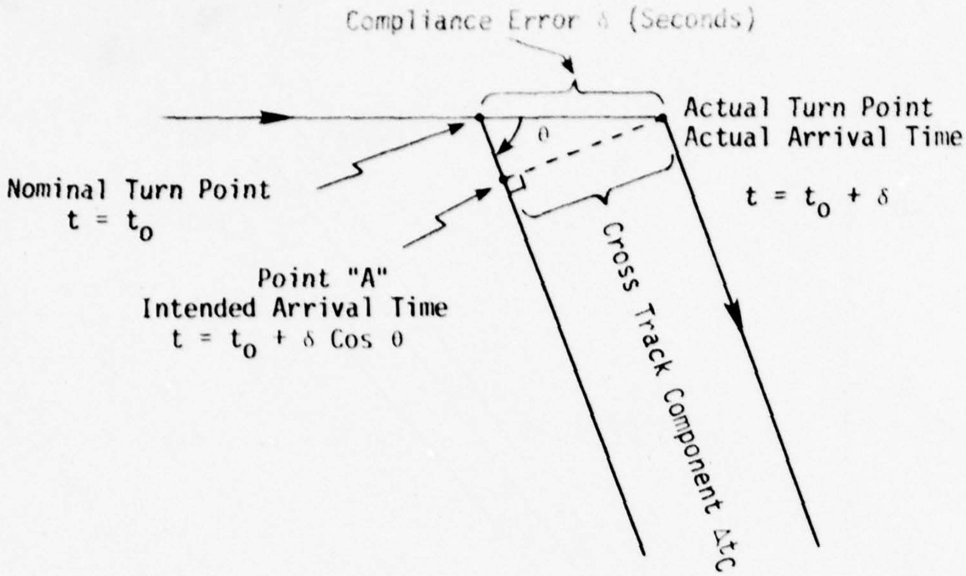


Figure C.5 Propagation of Compliance Error

The along track component of compliance error is the difference between the arrival time at the actual turn point and the intended arrival time at Point "A", which is the projection of the turn point on the intended route. Thus, the along track component is

$$\Delta t_A = t_o + \delta - (t_o + \delta \cos \theta) = \delta(1 - \cos \theta).$$

In each case (along and cross track), the resulting compliance error component is combined with other along and cross track errors on the subsequent leg in a Root-Sum-Square (RSS) fashion.

The primary purpose of this analysis is to determine arrival time control accuracy at a point. Nominally, this would concern along track control errors only. However, at each turn point any cross track error which exists propagates to some degree into the along track direction of the next leg. This is true at any turn point, including final approach course intercept. Figure C.6 illustrates this relationship.

From the figure it can be seen that, having been off course by the amount λ, an aircraft travels a different distance to the course intercept point on the next leg than it would have had it been on course. This error is as follows:

$$\Delta d_A = \frac{\lambda}{\sin\theta} - \frac{\lambda}{\tan\theta} = \lambda \frac{1-\cos\theta}{\sin\theta}$$

$$\Delta d_A = \lambda \tan \frac{\theta}{2}$$

Therefore, any cross track error component propagates into the along track direction, and thus becomes a time control error component, in the amount of the tangent of one-half of the turn angle. Total time control error is then found by computing the RSS of all components, including this cross track error contributor.

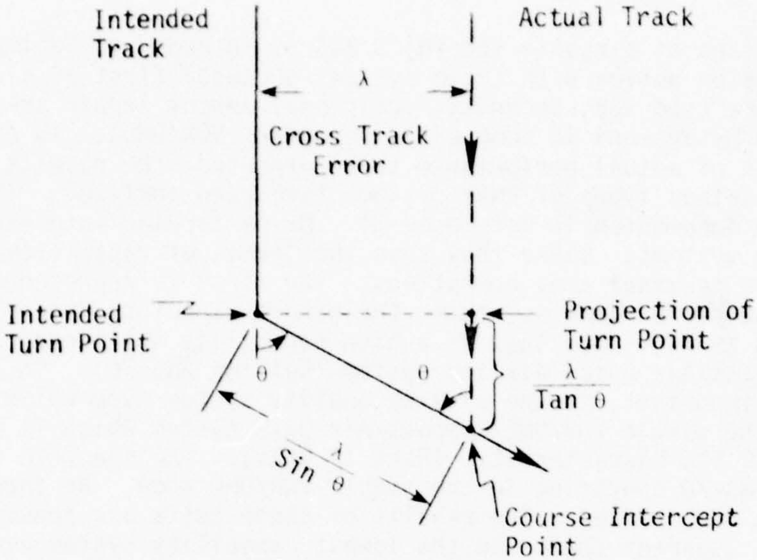


Figure C.6 Cross Track Error Propagation Into Along Track Dimension

In order that RNAV M&S procedures can be analyzed in a manner comparable to the radar vector case, reasonable estimates of RNAV system performance in an M&S environment must be obtained. FAA Advisory Circular AC 90-45A (Reference 10) states the minimum required RNAV system performance in the terminal environment in terms of subsystem error magnitudes, which are assumed to be independent and additive in an RSS Manner. These components are listed in Table C.3 (1σ values). To put these in perspective with respect to Table C.2, which lists the 1σ levels for other component error sources, consider that at a range of 20 miles from the reference VORTAC, cross track errors may be in excess of 0.8 mi (1σ) and along track errors in excess of 0.6 mi (1σ) (exact values depend on geometry). In actual practice, RNAV performance would be expected to be better than the minimum standard. This would in particular be expected of RNAV systems intended for use in air carrier (and business jet) aircraft, which make up

Table C.3. Area Navigation Minimum Capability (Reference 10)

Terminal Area One Sigma Values		
VOR Error		1.78°
DME Error		0.25 mi
	or	1.5% of Range
Computer Error		0.25 mi
Pilotage Error		0.50 mi

nearly all operations at airports for which M&S is intended to be implemented. Performance should be better with these systems because, first of all, higher quality sensors are used and, secondly, additional sensor inputs are available (Compass/Air Data System and in some cases redundant VOR/DME). In order to obtain an estimate of actual performance to be expected, the results of recent flight tests of various types of RNAV systems have been analyzed. The flight test programs are documented in Reference 31. Of particular interest are the results for three systems, since they span the levels of capability to be expected in future terminal area operations. The first is representative of the low end of the performance spectrum, the single waypoint, general aviation RNAV system (King KN-74). The last is a high capability multisensor (dual VOR/DME plus Compass/Air Data) airline system (Collins ANS-70). In the middle, and perhaps most important, is the airline quality system type which will be most prevalent, the single VOR/DME/Compass/Air Data system which is representative of the basic ARINC 583 Characteristic (Mark 13 RNAV). The specific system tested was the Collins ANS-70 operating in the single VOR/DME mode. No inertial reference systems were tested. The results of these tests are presented in Table C.4. It is apparent that even the lowest capability system performs better

Table C.4 RNAV System Flight Test Results

One Sigma Values -- Terminal Area Operations		
	Cross Track Error	Along Track Error
General Aviation	0.48 nmi	0.42
Corporate/Airline	0.30	0.26
Multisensor	0.15	0.14

than the basic requirement (0.48 nm cross track error is less than the pilotage error component alone as stated in AC 90-45A, not even considering the other error components). The other systems are obviously even better.

For the study of Metering and Spacing with RNAV, only the cross track component is of direct interest. The along track component does, however, directly affect 4D RNAV performance, and so will be discussed later. For purposes of this M&S analysis, the cross track error value for the basic airline system (0.30 nm, 1σ) will be used since that system is representative of the majority of systems to be expected in the near future. In the analysis of 4D RNAV M&S performance, however, the values for the multisensor system (0.15 nm cross track, 0.14 nm along track, 1σ) will be used since the multisensor system is representative of the more sophisticated 4D RNAV system to be expected in the later time periods.

The RNAV Metering and Spacing procedures analyzed here are the usage of clearances to a waypoint at a specified bearing inbound. The alternative, the use of the "Direct-To" feature, was not considered, not that it is not a viable candidate, but because the other procedure lessens controller workload since the messages are no longer as time critical; e.g. an M&S control command may

be communicated many seconds ahead of the point where the turn is to start, and therefore at the controller's convenience. Using standard radar vector techniques, or the RNAV "Direct-To" message, the message must be precisely timed in anticipation of the point where the maneuver is to begin, requiring greater controller involvement. Since the actual timing of the turn initiation point is no longer dependent on the compliance factor (4 seconds, 1σ from Table C.2), but is instead dependent on the airborne equipment, turn initiation accuracy is controlled by the system cross track accuracy (0.3 nm, 1σ).

Effects of Arrival Time Errors on Controllability

Under radar vector conditions, a control command is issued at a particular point in time in order to eliminate the time control errors which have built up since the last command, as well as to cause a predetermined delay in the arrival of the aircraft at the gate for spacing purposes. Two factors influence errors in the resulting action by the aircraft: the error of the surveillance system, and the pilot/controller time response variability about a nominal response time (compliance error). As flight progresses, other errors accumulate due to winds, sensor errors, etc. Each of these error sources is independent, and so their statistics add in a root-sum-square fashion. When the next control command is issued, the accumulated errors are compensated. After the last command, no further compensation occurs, and so the accumulated error as the aircraft crosses the gate is the gate delivery error, which is related to interarrival error, the quantity upon which airport arrival capacity depends. Successful operation of the Metering and Spacing function depends upon the ability of the system to selectively delay aircraft arrival time at the gate. Therefore a certain amount of delay flexibility (called controllability) is required. The raw controllability of a route configuration may be computed by simply subtracting the shortest path length from the longest and applying nominal speeds. However, this degree of controllability is not available 100% of the time due to the errors which accumulate as each flight progresses. For example, if an aircraft were assigned the maximum delay route, but due to winds, etc. wandered off that route on a shorter route, the aircraft would be unavoidably early. Wandering in the other direction, to achieve a longer route, would have no effect on gate arrival time since the M&S system would sense the error and be able to shorten the route at the next control point. Since the time control error quantities are described in probabilistic terms (95.44% confidence level --2σ), it is also possible to determine the degree of controllability available (as diminished by error) to the 95.44% confidence level.

Finding 2σ controllability given deterministic controllability and 2σ time control errors does not amount to simply subtracting off the 2σ error value. This results since the errors affect controllability only at the limits of control (shortest and longest routes). As stated above, the ability to achieve maximum delay, for example, is affected only when the errors shorten the path, not when they lengthen it. Similarly, the ability to achieve minimum delay is affected when the errors lengthen the path rather than when they shorten it. Thus, controllability is limited by the errors only when they occur in one sense, and not the other. Therefore, the amount of error to be subtracted off the longest path length to achieve 95.44% confidence in having the availability of at least that path length would not be the 2σ value but rather the 1.69σ value. This value represents the point on the Gaussian distribution beyond which 4.56% of occurrences lie (hence 100-4.56% = 95.44% confidence level). However,

what we are truly interested in is knowledge to a specified confidence level of the difference in path lengths (controllability), not the length of a specific path. Figure C.7 illustrates a simple case for purposes of discussion. Neglecting velocity control, the limits of control in this case are paths PQR (shortest) and PQ'R (longest). Without errors, the controllability available is the difference in path lengths, shown as "C" on the Figure. However, random errors e_1 and e_2 limit the path lengths available to those shown in the example (dotted lines). Given the values that e_1 and e_2 might adopt at any given moment, the resulting controllability would be:

$$c = C - (e_1 + e_2), \text{ where } C = L_{PQ'R} - L_{PQR}$$

The e_1 and e_2 terms are however independent, random variables, and so their statistics add in an RSS fashion rather than algebraically:

$$\sigma_c = \sqrt{\sigma_1^2 + \sigma_2^2}, \text{ where } \sigma_1^2 = E(e_1^2)$$

Therefore, the 95.44% controllability is:

$$c_{95.44} = C - 1.69\sqrt{\sigma_1^2 + \sigma_2^2}$$

or, where $\sigma_1 = \sigma_2$

$$c_{95.44} = C - 1.69\sqrt{2}\,\sigma$$

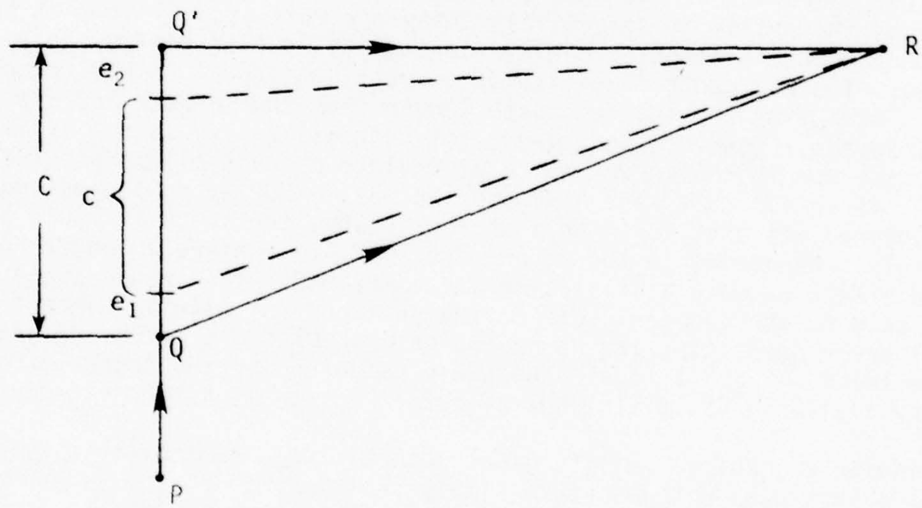


Figure C.7 Controllability Example

The approach taken to assessing controllability was to examine the longest and shortest paths independently. This was done because the control error terms are highly sensitive to geometry, and the geometry of the longest and shortest paths are far different. Also, the long path can (and does in this case) have more control points than the short path, and so controllability can't be assessed segment by segment, but only as the difference between the longest and shortest paths, as degraded by delivery errors. (In Figure C.7 each

extreme has one control point, Q and Q'). Therefore, while the σ value for the point in question is known, the σ for the correspondsing point on the other extreme may not exist, since a comparable point may not exist. As a result, the path length ℓ was taken to be the nominal length L degraded (longest made shorter, shortest made longer) by one-half of the total contribution. That is to say that ℓ (degraded path length) becomes:

$$\ell_{95.44} = L - (+)\ 1.69\sqrt{2}\sigma/2$$

Then, $c_{95.44} = \ell_{long} - \ell_{short} = C - 1.69\sqrt{2}\sigma$, as before,

if the σ values for both paths were the same. If the two σ values were not the same, then this method is slightly inexact.

Two different types of control points exist in the control geometry illustrated in Figure C.2, which is functionally almost identical to that in Reference 30. At the first type of control point, timing errors which have accumulated along the leg to the control point are corrected by M&S through adjustment of the location of the control point. For example, referring to that figure, an aircraft which is travelling from Point A towards Point L will have its accumulated errors corrected by selection of the point where the turn towards P is initiated. At the second type of control point, control is not exercised through adjustment to the point itself, but by path selection adjustment as the aircraft departs the point. The example of this type is the P-arc. No control action is taken until the aircraft crosses the P-arc, at which time a departure heading is issued intended to compensate for the delivery error to the P-arc.

In the first case above (active control point), delivery errors are assumed to be cancelled out by the adjustment to the point. The controllability at the point is first tested to determine whether enough is available to compensate for the error 95.44% of the time. If it could not, it would invalidate the particular design concept being analyzed. (The exception is the final approach segment to the Gate, Point G, where the available speed controllability is insufficient to compensate for accumulated error, and Gate Delivery error results). If the error can be compensated, path length is degraded accordingly, and time error for the subsequent leg is set to zero (plus surveillance and compliance components).

In the second case above (fixed control point), accumulated error is likewise compared to controllability over the immediately following leg (to the 95.44% level). If it cannot be compensated, the design would again be invalidated. Since the compensation does not occur until after the point is passed, the inbound path length is not degraded. However, the outbound path length is degraded for both delivery errors to that point and accumulated additional errors at the subsequent point.

Gate Delivery Error

Gate delivery error results from the accumulation of arrival time errors over the very last route segment, which terminates at the gate. When these errors cannot be compensated through speed control, a net Gate delivery error results. However, whatever speed controllability there is may be used

to offset some of the delivery error. To the first approximation, Gate delivery error (2σ) equals accumulated arrival time error less one-half of the controllability (since speed would nominally be reduced at the midpoint of the path, the correction factor is one-half of the total controllability).

C.1.5 Controllability and Delivery Error Results

This section describes the results of the methodology of Section C.1.4 when applied to study the three cases of interest: M&S with radar vectors, M&S with RNAV, and M&S with 4D RNAV. The detailed analyses are summarized in Tables C.5 (radar vectors), C.6 (RNAV) and C.7 (4D RNAV). Only one will be reviewed here for brevity, and then the summary results will be presented.

Analysis

Table C.5 contains the analyses of the longest and shortest paths using the basic radar vector M&S technique. The analysis table identifies each leg, states speed, heading, travel time and other characteristics. The first column (from Points A to L) shows the accumulated along track error (Item 8) component at L, which includes all the components in Figure C.4 plus compliance error, as affected by Item 7, turn angle. Item 9 shows cross track error due to Table C.2 contributors, and Item 10 includes compliance error. The turn angle to the next track (Item 11) is used in deriving total arrival control error at Point L (2σ). The amount to be corrected by path length degradation (1.69σ) is then shown, followed by the raw controllability available at the control point, which must be greater than $1.69\sqrt{2}\,\sigma$ to assure (95.44%) that sufficient control exists for error compensation. Since no correction requirement can carry over from the last leg, Item 16 is zero and Item 18, total correction, equals Item 13. The nominal path length in Item 6 is then reduced by $\sqrt{2}/2$ times Item 18 to yield 95.44% confidence path length (in seconds). Delivery error, having been compensated, is zero.

The second leg of the procedure, from point L to the P-arc, is similar to the first leg until Item 11 is reached. The turn angle to the next track is zero, so cross track error does not contribute to time control error, although it would be corrected on the subsequent leg. Since the P-arc is a fixed control point, all of the compensation would occur on the subsequent leg, hence the entry in Item 15. Also, Item 18 will be zero, and Item 20, delivery error, contains the time control error from Item 12.

The third leg, from the P-arc to Point P, will be used to compensate for both the errors on the previous leg, plus the newly accumulated errors. The errors on the third leg are stated in Items 12 and 13, which is compared with available controllability to insure the correction can be made. The error from the previous leg is entered in Item 16, which is also checked against available controllability. The errors are combined in Item 18 and used to adjust path length, Item 19.

Table C.5 Radar Vector M&S Analyses

Longest Path - Radar Vectors

	Leg 1	Leg 2	Leg 3	Leg 4
1. "From" Point	Point A	Point L	P-arc	Point P
2. Heading	050°	185°	185°	255°
3. "To" Point	Point L	P-arc	Point P	Point G
4. Path Length	13.0 mi	10.7 mi	1.8 mi	5.0 mi
5. Speed	180 kt	180 kt	160 kt	160/150 kt
6. Nominal Travel Time	260.0 sec	214.0 sec	40.5 sec	120.0 sec
7. Turn Angle - Previous Track	70°(Lyons)	135°	0°	40°
8. Along Track Error (Time)	30.2 sec	28.3 sec	5.2 sec	14.6 sec
9. Cross Track Error - 6.63° (Dist.)	1.50 mi	1.24 mi	0.21 mi	0.58 mi
10. Cross Track Error - Total (Time)	30.9 sec	25.4 sec	4.7 sec	14.8 sec
11. Turn Angle - Next Track	135°	0°	40°	0°
12. Total Time Control Error - 2σ	80.5 sec	28.3 sec	5.5 sec	14.6 sec
13. Correct at Control Point - 1.69σ	68.0 sec	0	4.6 sec	12.3 sec
14. Controllability at Control Point ($\geq \sqrt{2} \times$ 13)	294(≥96.1)	0	38.6(≥6.5)	7.5(<17.4X) Speed Control can't correct
15. Correct on Next Leg - 1.69σ	0	23.9 sec	0	-
16. Correction for this Leg (Previous 15)	0	0	23.9 sec	-
17. Controllability for this Leg ($\geq \sqrt{2} \times$ 16)	0	-	38.6(≥33.8)	-
18. Total Correction This Leg - RSS (13 + 16)	68.0	0.0 sec	24.3 sec	12.3 sec
19. 95.44% Confidence Path Length (6 - 18 $\times \sqrt{2}/2$)	211.9 sec	214.0 sec	23.3 sec	111.3 sec Total = 560.5
20. Delivery Error	0	28.3 sec	0	14.6 sec

Gate Delivery Error = 14.6 - 7.5/2 = 10.8 sec. (2σ)

Table C.5 Radar Vector M&S Analyses (Continued)

Shortest Path - Radar Vectors

	Leg 1	Leg 2	Leg 3
1. "From" Point	Point A	N-Departure	P-arc
2. Heading	090°	135°	210°
3. "To" Point	Towards N	P-arc	Point G
4. Path Length	4.7 mi	2.7 mi	4.3 mi
5. Speed	180 kt	180 kt	160/150 kt
6. Nominal Travel Time	94.0 sec	54.0 sec	96.8 sec
7. Turn Angle - Previous Track	30°(Lyons)	45°	75°
8. Along Track Error (Time)	11.1 sec	7.0 sec	12.8 sec
9. Cross Track Error - 6 63° (Dist.)	0.54 mi	0.31 mi	0.50 mi
10. Cross Track Error - Total (Time)	11.5 sec	8.4 sec	13.6 sec
11. Turn Angle - Next Track	45°	75°	45°
12. Total Time Control Error - 2σ	12.1 sec	9.5 sec	14.0 sec
13. Correct at Control Point - 1.69σ	10.2 sec	0	11.8 sec
14. Controllability at Control Point ($\geq \sqrt{2} \times$ 13)	164($\geq$14.4)	0	0 (<16.7X) No options
15. Correct on Next Leg - 1.69σ	0	8.0 sec	-
16. Correction for this Leg (Previous 15)	0	0	8.0 sec
17. Controllability for this Leg ($\geq \sqrt{2} \times$ 16)	0	-	38.2($\geq$11.3)
18. Total Correction This Leg - RSS (13 + 16)	10.2 sec	0.0	14.3 sec
19. 95.44% Confidence Path Length (6 + 18 $\times \sqrt{2}/2$)	101.2 sec	54.0 sec	106.9 sec Total = 262.1
20. Delivery Error		9.5 sec	14.0 sec
Gate Delivery Error = 14.0 - 6.4/2 = 10.8 sec (2σ)			
Controllability = 560.5 - 262.1 = 298.4 sec. (95.44%)			

Table C.6 RNAV M&S Analysis

Longest Path - RNAV (0.6 nm System, 2σ)

	Leg 1	Leg 2	Leg 3	Leg 4
1. "From" Point	Point A	Point L	P-arc	Point P
2. Heading	050°	185°	185°	255°
3. "To" Point	Point L	P-arc	Point P	Point G
4. Path Length	13.0 mi	10.7 mi	1.8 mi	5.0 mi
5. Speed	180 kt	180 kt	160 kt	160/150 KT
6. Nominal Travel Time	260 sec	214.0 sec	40.5 sec	120 sec
7. Turn Angle - Previous Track	70°(Lyons)	135°	0°	40°
8. Along Track Error (Time)	30.8 sec	32.2 sec	5.2 sec	14.7 sec
9. Cross Track Error (Dist.)	0.6 mi	0.6 mi	0.6 mi	0.6 mi
10. Cross Track Error - Total (Time)	12.0 sec	12.0 sec	13.5 sec	14.4 sec
11. Turn Angle - Next Track	135°	0°	40°	0°
12. Total Time Control Error - 2σ	42.3 sec	32.2 sec	7.1 sec	14.7 sec
13. Correct at Control Point - 1.69σ	35.7 sec	0	6.0 sec	12.4 sec
14. Controllability at Control Point ($\geq \sqrt{2} \times$ 13)	294($\geq$50.5)	0	38.6($\geq$8.1)	7.5(<17.6X) Speed Control
15. Correct on Next Leg - 1.69σ	0	27.2 sec	0	- Can't Correct
16. Correction for this Leg (Previous 15)	0	0	27.2 sec.	-
17. Controllability for this Leg ($\geq \sqrt{2} \times$ 16)	0	-	38.6($\geq$38.4)	-
18. Total Correction This Leg - RSS 13 + 16	35.7 sec	0	27.8 sec	12.4 sec
19. 95.44% Confidence Path Length (6 - 18 $\times \sqrt{2}/2$)	234.8 sec	214.0 sec	20.9 sec	111.2 sec Total = 580.9
20. Delivery Error	0	32.2 sec	0	14.7 sec
Gate Delivery Error = 14.7 - 7.7/2 = 10.9 sec. (2σ)				

Table C.6 RNAV M&S Analysis (Continued)

Shortest Path - RNAV (0.6 nm System, 2σ)

	Leg 1	Leg 2	Leg 3	Radar Vector Alternate Leg 3
1. "From" Point	Point A	N-Departure	P-arc	P-arc
2. Heading	090°	135°	210°	210°
3. "To" Point	Towards N	P-arc	Point G	Point G
4. Path Length	4.7 mi	2.7 mi	4.3 mi	4.3 mi
5. Speed	180 kt	180 kt	160/150 kt	160/150kt
6. Nominal Travel Time	94.0 sec	54.0 sec	96.8 sec	96.8 sec
7. Turn Angle - Previous Track	30°(Lyons)	45°	75°	75°
8. Along Track Error (Time)	11.1 sec	7.5 sec	14.4 sec	12.8 sec
9. Cross Track Error (Dist)	0.6 mi	0.6 mi	0.6 mi	0.50 mi
10. Cross Track Error - Total (Time)	12.0 sec	12.0 sec	13.5 sec	13.6 sec
11. Turn Angle - Next Track	45°	75°	45°	45°
12. Total Time Control Error - 2σ	12.2 sec	11.9 sec	15.4 sec	14.0 sec
13. Correct at Control Point - 1.69σ	10.3 sec	0	13.0 sec	11.8 sec
14. Controllability at Control Point ($\geq\sqrt{2}\times$ 13)	164($\geq$14.5)	0	0(<18.4X)No	0(<16.7X)
15. Correct on Next Leg - 1.69σ	0	10.0 sec	- options	-
16. Correction for this Leg (Previous 15)	0	0	10.0 sec	10.0 sec
17. Controllability for this Leg ($\geq\sqrt{2}\times$ 16)	0	-	38.2(>14.1)	38.2($\geq$14.1)
18. Total Correction This Leg - RSS (13 + 16)	10.3 sec	0.0	16.4	15.5
19. 95.44% Confidence Path Length (6 + 18 $\times\sqrt{2}/2$)	101.3 sec	54.0 sec	108.4 Total=263.7	107.7 Total 263.0
20. Delivery Error	0	11.9 sec	15.4 sec	14.0
Gate Delivery Error = 15.4 - 6.4/2= 12.2 sec (2σ)				
Controllability = 580.9 - 263.7 = 317.2 sec. (95.44%)				
With Radar Vector to Gate: Gate Delivery Error = 14.0 - 6.4/2 = 10.8 sec. (2σ)				
Controllability = 580.9 - 263.0 = 317.9 sec. (95.44%)				

Table C.7 4D RNAV M&S Analysis

Longest Path - 4D RNAV (0.3 nm System, 2σ)

	Leg 1	Leg 2	Leg 3	Leg 4	
1. "From" Point	Point A	Point L	P-arc	Point P	
2. Heading	050°	185°	185°	255°	
3. "To" Point	Point L	P-arc	Point P	Point G	
4. Path Length	13.0 nm	10.7 mi	1.8 mi	5.0 mi	
5. Speed	180kt	180kt	160kt	160/150kt	
6. Nominal Travel Time	260.0 sec	214.0 sec	40.5 sec	120.0 sec	
7. Turn Angle - Previous Track	70°(Lyons)	135°	0°	40°	
8. Along Track Error (Time)	6.0 sec	6.0 sec	6.8 sec	7.2 sec	
9. Cross Track Error (Dist)	0.3 nm	0.3 nm	0.3 nm	0.3 nm	
10. Cross Track Error - Total	6.0 sec	6.0 sec	6.8 sec	7.2 sec	
11. Turn Angle - Next Track	135°	0°	40°	0	
12. Total Time Control Error - 2σ	11.9 sec	6.0 sec	6.4 sec	7.2 sec	
13. Correct at Control Point - 1.69σ	10.0 sec	0	5.4 sec	6.1 sec	
14. Controllability at Control Point ($\geq\sqrt{2}$x 13)	294($\geq$14.2)	0	38.6($\geq$9.0)	7.5(<8.6X)	Speed Control
15. Correct on Next Leg - 1.69σ	0	5.1 sec	0	-	Can't Correct
16. Correction for This Leg (Previous 15)	0	0	5.1 sec	-	
17. Controllability for this Leg ($\geq\sqrt{2}$x 16)	0	-	38.6($\geq$7.2)	-	
18. Total Correction this Leg - RSS (13 + 16)	10.0 sec	0	7.4 Sec	6.1 sec	
19. 95.44% Confidence Path Length (6 - 18 x $\sqrt{2}/2$)	252.9 sec	214.0 sec	35.3 sec	115.7 sec	Total 617.9 sec
20. Delivery Error	0	6.0 sec	0	7.2 sec	
Gate Delivery Error = 7.2 Sec. (2σ)					

Table C.7 4D RNAV M&S Analysis (Continued)

Shortest Path - 4D RNAV (0.3 nm System, 2σ)

	Leg 1	Leg 2	Leg 3
1. "From" Point	Point A	N-Departure	P-arc
2. Heading	090°	135°	210°
3. "To" Point	Towards N	P-arc	Point G
4. Path Length	4.7 mi	2.7 mi	4.3 mi
5. Speed	180 kt	180 kt	160/150 kt
6. Nominal Travel Time	94.0 sec	54.0 sec	96.8 sec
7. Turn Angle - Previous Track	30° (Lyons)	45°	75°
8. Along Track Error (Time)	11.0 sec*	6.8 sec*	6.8 sec
9. Cross Track Error (Dist)	0.3 mi	0.3 mi	0.3 mi
10. Cross Track Error - Total (Time)	6.0 sec	6.0 sec	6.8 sec
11. Turn Angle - Next Track	45°	75°	45°
12. Total Time Control Error - 2σ	11.3 sec	8.2 sec	7.4 sec
13. Correct at Control Point - 1.69σ	9.5 sec	0	6.2 sec
14. Controllability at Control Point ($\geq\sqrt{2}\times$ 13)	164($\geq$13.5)	0	0(<8.8X) No Options
15. Correct on Next Leg - 1.69σ	0	6.9 sec	-
16. Correction for this Leg (Previous 15)	0	0	6.9 sec
17. Controllability for This Leg ($\geq\sqrt{2}\times$ 16)	0	-	38.2(>9.8)
18. Total Correction this Leg - RSS 13 + 16	9.5	0	9.3 sec
19. 95.44% Confidence Path Length (6 + 18 $\times\sqrt{2}/2$)	100.7 sec	54.0 sec	103.4 sec Total = 258.1
20. Delivery Error	0	8.2 sec	7.4 sec
Gate Delivery Error = 7.4 sec. (2σ)			
Controllability = 617.9-258.1 = 359.8 sec. (95.44%)			

* On first two legs the object waypoint is too far removed for 4D time control to be effective at departure point. Therefore, standard errors are applied.

The last leg, to the Gate (Point G), proceeds as before with time control error as Item 12. The controllability available from speed control is not sufficient to correct for the error (Item 14), and so a net delivery error results in Item 20. On the bottom line the raw delivery error is corrected for the effect of speed control to yield net gate delivery error (2σ). Total path length (95.44% confidence level) is listed in Item 19 off to the far right. This entire process is repeated, as shown in the second part of Table C.5, for the shortest path length, yielding gate delivery error in that case and path length, from which controllability is determined and listed on the bottom line.

Results

The results of the analyses summarized in Tables C.5 through C.7 show two definite RNAV effects, both of which result from the same cause: that RNAV is a more accurate control tool (in terms of deviations from intended track) than radar vectors over all but the shortest paths. The dominant radar vector aggregate cross track error term of 6.63° (2σ) quickly exceeds the 0.6 mi (2σ) cross track error term expected to be typical of air carrier type RNAV systems, as path length exceeds five miles. Even the errors measured in flight tests of a low cost general aviation system (0.96 mi, 2σ) are exceeded for path lengths greater than eight miles. The other significant contributor to cross track error affecting short path lengths is compliance error, which is slightly greater in the RNAV case (0.6 mi, versus 8 seconds = 0.4 mi at 180 kt for radar vectors). As illustrated in Figure C.5 this error only significantly impacts cross track error when turn magnitude is large. The

Table C.8 M&S Controllability (95.44% confidence)

Region	Radar Vector M&S	M&S+RNAV	M&S+4D RNAV
Downwind/Base Leg	270.7 sec	293.5 sec	312.2 sec
Final Approach Intercept	27.7 sec	23.7 sec	47.6 sec
Overall	298.4 sec (5.0 min)	317.2 sec (5.3 min)	359.8 sec (6.0 min)

Table C.9 M&S Gate Delivery Accuracy

	Radar Vector M&S		M&S+RNAV		M&S+4D RNAV	
Control Extreme:	Long	Short	Long	Short	Long	Short
Gate Delivery Error (2σ)	10.8 sec	10.8sec	10.9sec	12.2 or10.8*sec	7.2sec	7.4sec
Interarrival Spacing (1σ)	7.6 sec	7.6sec	7.7sec	8.6 or 7.6*sec	5.1sec	5.2sec
Earlier Analyses (1σ)	11 or 8 sec		11 or 8 sec		5 sec	

* Smaller value presumes use of one radar vector command for final approach intercept.

two effects of this RNAV control accuracy are that RNAV significantly improves controllability over a given geometry while maintaining approximately equivalent gate delivery accuracy. These results are shown in Tables C.8 and C.9.

Table C.8 shows that RNAV improves overall controllability by several percent, from 5.0 to 5.3 minutes. All of the increase occurs in the downwind base leg area, the area of major time control activity. The controllability in the final approach intercept area, the "fine tuning" area, decreases slightly. Table C.9 shows the gate delivery error at the extremes of control, the longest and shortest paths. Over the longest path, RNAV shows virtually no effect; the 2σ error is 0.1 second larger in the RNAV case. Over the shortest path, gate delivery error increases somewhat with RNAV, from 10.8 to 12.2 seconds. However, this increase only occurs when the very shortest path is used; all paths in between the shortest and longest would exhibit gate delivery errors similar to the longest path, 10.9 seconds. Furthermore, when the shortest path must be used, gate delivery accuracy can be reduced to 10.8 seconds through substitution of one radar vector command for one RNAV command (final approach intercept), as shown in Table C.6. Therefore, RNAV procedures can be implemented without any detectable effect on gate delivery accuracy and will result in improved controllability.

The effect of 4D RNAV as an M&S control tool is quite dramatic. Not only does the usage of 4D control, as provided by an advanced RNAV capability (0.3 mi, 2σ-- as proven during recent flight tests), provide even more accurate gate delivery time; an added bonus is the dramatic increase in controllability which also results, 6.0 minutes as opposed to 5.0 minutes for radar vector M&S. Significant increases occur in both the downwind/base leg area and the final approach intercept area.

Note that the 4D benefit may be achieved using either DABS or ATCRBS surveillance, since even the ATCRBS accuracy (0.25°) is sufficient to provide adequate surveillance for a 4D M&S system. Raw sensor accuracy would be better than 2 sec. (1σ), and the tracking algorithm would significantly improve that.

The gate delivery accuracies determined in the present study are put in perspective relative to earlier analyses of M&S potential in Table C.9. Reference 32 derives values for one sigma interarrival error of 11 seconds for M&S and 5 seconds for 4D time control. Reference 30 lists an M&S interarrival control error of approximately 8 seconds as the target. Cockpit simulator studies, Reference 33, resulted in a 4D RNAV interarrival time control error of 5.4 seconds. Table C.9 lists the results of the present analysis in terms of one sigma interarrival control accuracy (interarrival accuracy equals absolute time control accuracy times $\sqrt{2}$). As the table shows, these latest results are consistent with the eight second (M&S) and five second (4D) results developed in the earlier studies.

C.1.6 Controller Workload Results

The Metering and Spacing procedure usually involves the use of five control points starting at point A on Figure C.2. A typical sequence of points is the departure from Point A, the turn towards point P, the turn towards Point P_1 at the P-arc, the final turn to intercept the final approach course, and the speed reduction after final approach intercept. In the case of basic radar vector M&S, the timing of each of these control messages is critical. The introduction of RNAV routes and procedures does not reduce the number of control points, since

the RNAV procedures were specifically designed to be compatible with the standard procedures. Also, if the simple RNAV "Direct To" command were used as the primary control command for M&S procedures, these commands would be just as time-critical as the radar vector commands. However by making use of the capability of all RNAV systems to proceed direct to a waypoint along a specific track bearing, the time-criticality of the control commands for all four turns would be far reduced. The M&S automation would provide the track bearing information to the controller ahead of the turn. The controller could issue the direct command at his convenience rather than within a very few seconds of the target turn point. While the message count remains the same, the organizational and communications burden on the controller is considerably relieved.

The same result with regard to non-critical timing would be expected with 4D RNAV. However, the need for the final M&S message,the speed reduction, is eliminated since the 4D system takes care of that. Therefore, the message count is reduced under 4D RNAV conditions. Countering the trend to lower workload levels with RNAV is the fact that RNAV and 4D messages contain more information: RNAV adds a waypoint name, and 4D adds an arrival time to that, although aircraft speed is removed. The basic M&S message would contain aircraft identifier, heading, speed and altitude. The waypoint name would not be expected to significantly complicate the message. Inclusion of arrival time (minutes, seconds) could increase the communications burden and the possibility for erroneous interpretation to a minor extent, until Control Message Automation is implemented. However, these factors would be expected to be outweighed by the advantages in terms of time-criticality.

The use of the 4D technique also requires that the airborne system be synchronized to the ground clock. However, this may be done at any time during, or before, the flight (a highly accurate airborne clock is not required), so workload level is not increased. Naturally, if DABS is in use the synchronization may be accomplished automatically.

C.1.7 Computer Requirements Impact

A previous study of the core requirement and execution time impacts of integrating RNAV procedures with Metering and Spacing appears in Reference 34, and is summarized in Reference 8. The core requirement impact is very small (450 words added onto a nominal 16,000 required for M&S), based on analysis of M&S procedures similar to those described herein. There was found to be no execution time impact. The display data block on the controller's scope must be enlarged slightly to accommodate the waypoint name (five characters).

No similar analysis exists for 4D RNAV core requirements and execution time impact. However, since the 4D function is really a very simple extension of the RNAV concept, and waypoint arrival times would be assigned within the workings of the basic M&S program even though they are not communicated to the controller, it seems that the 4D impact would be limited to again slightly enlarging the display data block to accommodate that new data.

C.2 CONTROL MESSAGE AUTOMATION SYSTEM COMPLEXITY IMPACT ASSESSMENT

C.2.1 Introduction

Control Message Automation (CMA) is intended to be a major ATC controller productivity enhancer. The CMA system will take advantage of the planned DABS data link and airborne control command display capability in order to automatically communicate computer-formulated commands upon ATC controller approval (routine approval shall probably be required as CMA is initiated, although it may be eliminated for certain command types, e.g. Metering and Spacing, as time progresses). CMA is one of the most important UG3RD automation enhancements since it has the potential for producing large reductions in controller workload, therefore reducing staffing costs.

Control Message Automation will eventually be used for several ATC purposes:

- Resolution of potential airspace conflicts, based upon a conflict prediction or alerting capability.
- Automating the routine control communications of M&S, and 4D M&S.
- Provision of routine control messages (altitude changes, speed changes, clearances, etc.)

The usage of SID/STAR procedures in general, and RNAV SID/STAR procedures in particular, will simplify the CMA task, just as they can be used at present to simplify the radar controller's task. Naturally, the CMA system can deliver amendments, in the form of parallel offsets, direct-to-procedures, deviations from specified altitude, etc, to the published procedure at any time, where such deviations are warranted.

The following sections will discuss further the CMA process, and the expected impact of RNAV on CMA system complexity.

C.2.2 CMA System Elements

A control message automation system may be thought of as consisting of six elements, as follows.

Automated Monitoring -- This function includes aircraft tracking, as done presently in the ARTS and NAS automated systems, although the surveillance system would be DABS rather than ATCRBS. In addition, however, many CMA functions would require association of the tracked aircraft with its intended route or path of flight, such that track deviation and flight progress are always known. For example, the M&S function requires knowledge of the aircraft with respect to the command track and intended arrival point.

Problem Recognition, or Strategy Development -- This function is highly dependent on the particular CMA function of interest. It is the conflict detection portion of a Conflict Alert or Conflict Prediction system. It is the arrival time determination logic in a Metering and Spacing system.

Control Action Decision -- It is at this stage that a specific decision as to the type of deviation from the present flight plan is required to achieve a specific objective; e.g. heading change, altitude change, speed change, or a combination.

Message Formulation -- At this point a specific message is formulated for delivery to the aircraft. A voice message for controller delivery, or DABS format message for automated delivery, or a combination of both would result.

Transmission and Verification -- At this point the message is forwarded to the controller's console or to the DABS site for transmission to the aircraft. A signal indicating successful transmission would be expected in return.

Compliance Monitoring -- Subsequent message generation would then be held up until the system determined whether or not the aircraft was, in fact, complying with the message transmitted. If so, the CMA function resumes. If not, a controller alert message would be sent to the control console, and a contingency control message intended to compensate for the aircraft inaction would be generated by the CMA function.

C.2.3 RNAV Impact Assessment

Only two of the above six elements of a CMA system would be affected to any degree by the presence of an RNAV flight plan. The "Control Action Decision" function is affected slightly, because RNAV provides two additional control options (parallel offset and direct-to). This may influence the control decision process for the following reasons. First, if an aircraft is on an RNAV flight plan, it is desirable to keep him on RNAV so that he may resume navigation easily after the situation has passed. Second, these lateral RNAV control instructions will be, in some cases, more desirable than an altitude reclearance from the point of view of the aircraft, or more desirable than a radar vector, which requires closer monitoring and usually more control messages, from the point of view of the ATC system. The net result is that recognition of RNAV flight plans would influence the design of the logic of the "Control Action Decision" phase. This should not significantly affect the computer resources required, however.

The other phase affected by RNAV is the "Message Formulation" phase, since the presence of RNAV capability requires that the system be capable of generating more types of messages. To obtain a better idea of the influence of RNAV on CMA requires a more detailed breakdown of message considerations, as follows.

Message Types -- Integration of RNAV adds two message types for conflict prevention (offset, direct-to) and one for M&S (direct-to at specified track bearing -- see Section C.1.2) to the number of messages for which capability must be provided.

Types of Computations -- The computations required to generate the RNAV messages are no more complex than those required for conventional control. For example, a parallel offset is no more difficult to generate than a radar vector procedure. RNAV actually simplifies the consideration of winds in the M&S system.

Messages per Conflict Incident -- A lateral maneuver with RNAV requires two messages: a parallel offset followed by a cancel offset, although they can be combined into one, such as by specifing the point (or elapsed distance or time) after which the offset is cancelled. Alternatively, a radar vector procedure requires at least two and sometimes three messages (depart track, roughly parallel track, return to track). On the average, RNAV would involve fewer messages.

Messages per Arrival for M&S -- In Appendix C it is shown that RNAV requires the same number of messages as radar vector M&S. In addition, 4D RNAV M&S uses one fewer message.

Routine Control Messages per Aircraft -- RNAV would have a minor effect on the number of routine control messages delivered. These include control messages, speeds, altitudes, altimeter barometric settings, etc. The RNAV effect is a slight reduction to message count, as demonstrated in the DABS channel capacity analysis in Appendix A.

RNAV SID/STAR Impact -- Where and when M&S is not in use, the existence of RNAV SID/STAR procedures will significantly reduce message counts in comparision to automated radar vectoring of the aircraft. Where amendments to the SID/STAR procedure are needed, the parallel offset or direct-to messages are very efficient means of achieving the needed deviations. Such reductions in message counts were not reflected in Appendix A, since LAX is presumed to be an M&S terminal, and so this discussion would not apply.

It is quite apparent that the integration of RNAV will require some additional effort in the development of CMA. Also, the resulting computer code will be slightly longer, reflecting the added complexity. However, execution time requirements may actually be shorter due to the reduction in message counts. Each of these effects are expected to be minor. They appear to be even more insignificant when viewed in the context that the "Control Decision" and "Message Formulation" sections of CMA constitute only a minor portion of the overall CMA function. The majority of computer resources are involved in the various other necessary aspects of Control Message Automation.

C.3 RNAV IMPACT ON CENTRAL FLOW CONTROL AUTOMATION PLANS

C.3.1 Introduction

The Central Flow Control (CFC) facility comprises a major part of the FAA Systems Command Center. The primary objectives of CFC are to prevent or minimize costly airborne delays which result from periods where aircraft demand exceeds capacity, and to prevent saturation of enroute airspace near large terminals due to excess arrival aircraft. Both excess demand and insufficient capacity can cause such situations. Insufficient terminal capacity may be either chronic (inability to service ordinary peak demands) or temporary, as caused by severe weather or shutdown of necessary navigational or ATC facilities.

C.3.2 Present Flow Control Procedures

The flow control process consists principally of two basic functions. The first is the collection of demand and capacity data and the recognition and forecasting of excess delay situations. The second is the coordination and control function to minimize the delay impact on operators and the ATC system. Basic flow control procedures are defined in two FAA Orders, References 25 and 26. These define the flow control process and procedures to be used. At present, three basic flow control procedures are used for the minimization of arrival/departure delays at major airports and prevention of airspace saturation.

Standard Intercenter Flow Control -- This is the process by which a ARTC center will recognize that the capacity of the center to absorb delaying arrival aircraft to a large terminal within its jurisdiction (or its capacity to absorb departing and enroute traffic within the existing route structure) is or will be exceeded. At that point, arrivals to the center from adjacent centers would be restricted. This is the standard, original flow control procedure. The CFC system was established to coordinate, expedite and minimize the aircraft operator impact of these activities.

Fuel Advisory Departures -- This is the process whereby aircraft bound for certain critical airports are given the option of accepting some of the anticipated delay on the ground prior to departure. This ground delay is then considered when determining an aircraft's position in the landing queue upon arrival to the terminal. The intent of the FAD procedure is to save fuel.

Quota Flow Control -- Quota Flow Control (Q Flow) is a more formalized version of the standard flow control technique. The action taken depends upon the location of the departure terminal relative to the Q Flow terminal, and aircraft operator desires. Upon saturation of the arrival center, arrival quotas will be set for that center and each adjacent center. Departures within those specific centers bound for the high delay terminal will ordinarily be assigned ground delay, although an operator may request air delay if he so desires. Long distance flights (originating beyond the adjacent centers) are delayed in the adjacent centers in order to not overload airspace. If, for reasons such as insufficient fuel, they desire to land at a different airport,

the ground delay experienced there counts toward airborne delay in determining quota priority. Fuel Advisory Departure procedures may be used in conjunction with Q Flow.

Proper execution and timing of such procedures depends upon comprehensive, timely and accurate data collection and delay prediction. Presently, such procedures are automated, although the traffic demand data included in the system is limited and not necessarily timely. Reference 27 documents the existing prototype air traffic flow control automation system (the Airport Information Retrieval System - AIRS). This system is primarily oriented towards predicting terminal saturation conditions; it does not spot potential enroute congestion points. The major source of data is the Official Airline Guide data tape, which is updated periodically. General aviation aircraft operations are included only as estimates, or historical percentages; no real time flight plan data is included. The Airport Reservations Office (ARO), also located in the Systems Command Center, furnishes real time inputs concerning changes to schedules and other traffic for ARO Terminals. Airport capacity data is taken from local daily estimates and projections periodically furnished by each terminal via teletype. The automated facility then estimates delays and holding stack requirements on demand, and will determine Quota Flow quota data. It also aids in accomplishing Fuel Advisory Departures by listing out up-to-date departure time estimates, and accepts revised departure time estimates in order to provide revised delay/holding stack results.

Since the existing AIRS system does not consider specific routings, there is no direct RNAV impact. Manual procedures are used for assigning weather or congestion avoidance routings, and an RNAV route structure would provide added rerouting options. Also, RNAV could be used in many cases to increase the available holding airspace by providing holding fixes at arbitrary points.

C.3.3 Future Flow Control Features

An automated flow control system is planned (Reference 28) which replaces the present AIRS system, and provides considerably improved data collection and forecasting services. The system will use the 9020A computer located at Jacksonville ARTCC, although the main flow control staff will remain at the Systems Command Center and operate the system remotely. Present plans include implementation of the system in two phases, the Basic System and the Enhancement Package. The end result will be a system with capabilities including direct links to each of the 20 ARTCC computers in order to provide real time updates to the OAG Traffic data base. Features to be provided will include traffic load summaries, delay predictions, demand predictions, computer generated flow control advisories, and message preparation and dissemination to the ARTCC's. In addition, the ability to provide traffic demand summaries at key enroute fixes shall be included. System activity is to be centered around the arrival/departure traffic at fifteen "pacing" airports which generate the preponderance of traffic delays. System capabilities will include the ability to automatically generate Fuel Advisory Departure detailed reports and Quota Flow reports and automatically transmit that data to the affected centers.

C.3.4 RNAV Impact on Future System

The future CFC system will accomplish much the same tasks as the existing system, except that the process will be more highly automated, and much more accurate, because the ARTCC direct computer communication capability will allow the flight plan data base to be kept much more current than is presently possible, and for several other reasons. The planned capability to provide projected fix loading data for various fixes in the enroute and terminal environments is a new capability. On the surface, it would appear that RNAV implementation would significantly impact the complexity of this task, since the RNAV routes will traverse different fixes than conventional routes. However, this is not the case. The exact routing of individual flights is not examined by this function. Instead, an ascribed general routing is established whereby if any of a set of 255 (maximum) fixes, which represent segments of center or terminal airspace, are traversed by the general or typical route or flight, that fix name would be attached to that flight plan record for future reference. The fact that RNAV and conventional routes between given city-pairs will not ordinarily deviate seriously from one will render the RNAV distinction to be of little importance for these purposes. Therefore, RNAV impact on CFC operations will be insignificant except that, as stated before, RNAV can be used to provide more holding airspace (in some cases), and to provide more flexibility in assigning reroutings for weather or congestion avoidance, which are manual procedures.

APPENDIX D

MLS SYSTEM IMPACT

D.1 INTRODUCTION

The present Instrument Landing System (ILS) was developed in the 1940s to meet the then current and projected operational requirements. To date, the ILS has provided highly useful service. However, the technical and operational limitations inherent in ILS impose constraints which are significant in todays terminal area environment.

Of primary concern are the multipath effects characteristic of the VHF/UHF bands of the ILS. These effects make siting of ILS systems difficult if not virtually impossible at some airports requiring precision landing aids. The multipath effects are realized as reflections from local obstructions, such as hangars and large aircraft near the runway, causing perturbations of the primary guidance signal. These perturbations are difficult to overcome in the VHF/UHF band.

The primary means of reducing multipath effects involves proper siting of the ILS antenna. This can be achieved through extensive site preparation which could be both difficult and costly. The multipath/siting problem is becoming an ever increasing concern as the number of airports requiring precision landing aids increases. This concern, together with the added benefits of wide area coverage and reduced minimums (especially in adverse weather conditions) has encouraged the development of MLS.

The increase in the density of traffic in the terminal area has emphasized the requirement for approach paths which differ from the straight-in approaches characteristic of ILS. This requirement stems from two factors: (1) the need for greater utilization of terminal airspace, and (2) the desire for reduced noise over populated areas. Both of these factors support the consideration of both curved approach and steeper descent paths (typical of STOL and VTOL aircraft). The additional approach path requirements dictate the need for a precision landing system providing volumetric navigation support.

These landing aid requirements have led to the Microwave Landing System (MLS) developmental program. The following objectives were established for the MLS program:

- Develop a new precision landing guidance system by 1977 which will have increased performance compared with today's UHF/VHF ILS system and will require less costly and stringent requirements for site preparation and installation.

- Develop a basic system with the capability of increased performance through modular additions so that the capability and cost can be tailored to satisfy differing requirements of various airports and users.

- Provide for curved, multiple approaches so that approach paths can be selected for minimum noise impact on the community consistent with aircraft flight characteristics. This improvement in flexibility of the service relates directly to the overall goal of improving performance.

- Provide a single standard for the signal-in-space which will satisfy the principal needs of the civil, military, and international users. Not only would this eliminate the additional costs of several proliferating systems, but it would add to the safety of emergency operations, permitting, for example, a precision approach of a civil aircraft at a military installation.

- Complete essential development at a sufficiently early date to ensure availability for evaluation by other ICAO members.

Analysis and experimentation has shown that many of the objectives enumerated above can be achieved at microwave frequencies where a narrow beam can be generated with a relatively small antenna. In 1967, the Radio Technical Commission for Aeronautics (RTCA) formed a special committee (SC-117) [42] to lay the ground rules and guidelines for the coordinated development of the MLS.

Basically, the MLS is an air derived system [42], that is, ground stations will generate and transmit coded signals which will enable an airborne receiver/processor unit to derive its precise azimuth angle, elevation angle and range data. This data will be suitable for display to the pilot or for use by an automatic flight control system. In addition, provision is made for the ground-to-air transmission of auxiliary data providing runway identification, the condition of the runway, the operational status of the guidance system, and weather data.

An important feature of the MLS design is that of modularity whereby configurations having different levels of performance capabilities and costs can be adapted to satisfy the diverse requirements of various users. Because of this performance modularity, all airframe and ground-based components of the system will be fully compatible with each other. This implies that in any particular operational situation, the service provided by any combination of a ground facility and an airborne unit is limited only by the capability of the less sophisticated of the two.

The coverage volume provided by the MLS is shown in Figure D.1. Current plans dictate that azimuth coverage be provided within a 120° sector symmetric about the extended runway centerline. The elevation angle ranges from 1.5° to 22° and the maximum DME range is 20 nm. The maximum altitude for MLS coverage is expected to be 20,000 ft. This coverage is adequate to support a wide variety of approach trajectories.

MLS position coordinates are defined with respect to a runway centered reference frame rather than the 360° north-referenced bearing system of RNAV. Slant range measurement is similar to the slant range available from DME. The additional measurement, elevation angle, is a substitute for the

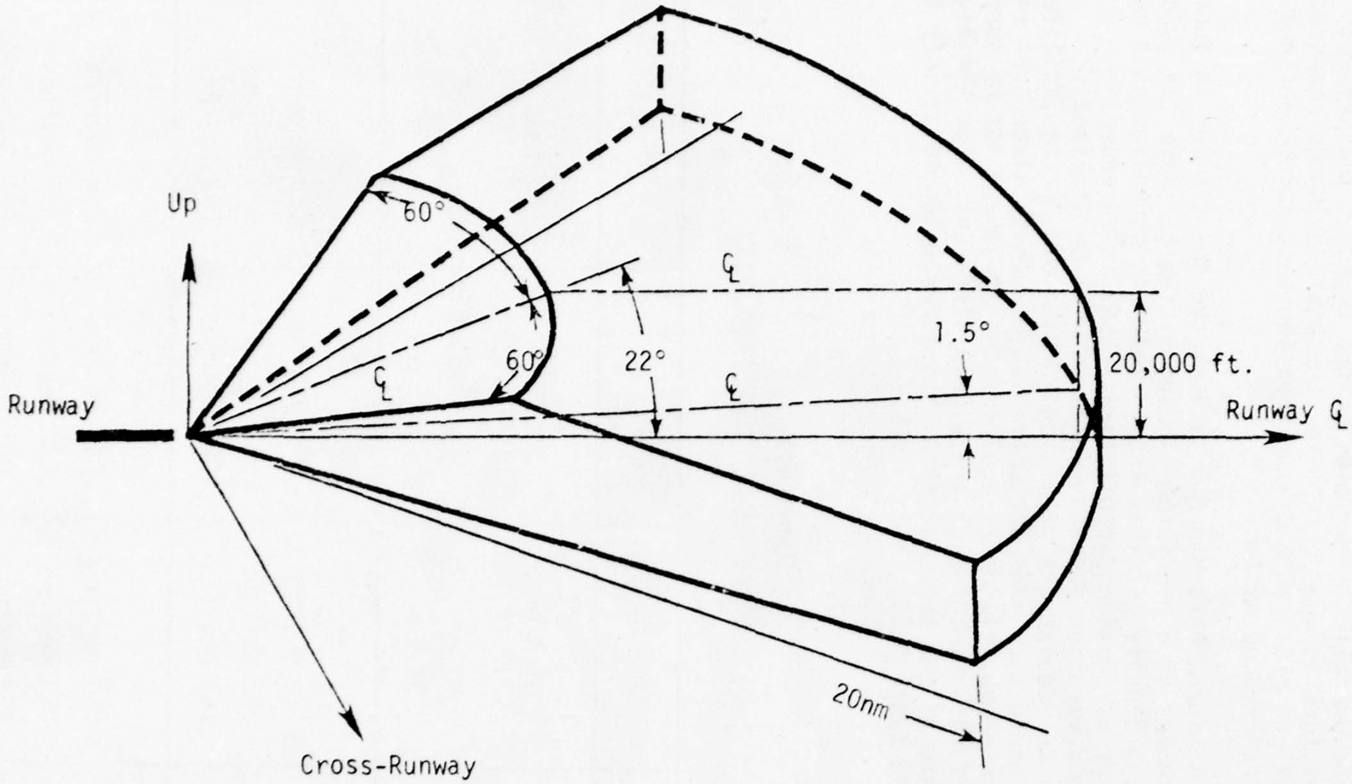


Figure D.1   MLS Coverage Region

altimeter. However, unlike the barometric altimeter, the MLS-derived altitude is computed with respect to the ground independent of the local barometric pressure setting. The overall similarities in the types of measurements insures that a common form is appropriate for the basic guidance computations required of both RNAV and MLS. Both of the equation sets can be defined in terms of a waypoint referenced system.

Though similar in form, RNAV and MLS systems are not similar in function. MLS is primarily intended as a precision landing system to serve the guidance requirements of a high density terminal area. RNAV was conceived as a means to provide point-to-point navigation capabilities. RNAV is intended to serve the enroute navigation function and also will be utilized in the terminal area to acquire the precision landing aid, or to facilitate approach procedures where such aids are unavailable. Thus, given that each system is designed to serve different requirements, it should not be surprising that the error specifications for each are widely different. For the high precision requirements of the terminal area, MLS is expected to satisfy the error budget shown in Table D.1.

Table D.1

RTCA [42] MLS Specifications (1σ)

Configuration Operational Use	D Cat. I	F Cat. II	K Cat. III
DME			
Bias	91.4 m (300 ft.)	30.5 m (100 ft.)	6.1 m (20 ft.)
Random	*	*	*
Total	91.4 m	30.5 m	6.1 m
AZ			
Bias	.125 degrees	.090 degrees	.036 degrees
Random	.065 degrees	.033 degrees	.024 degrees
Total	.141 degrees	.096 degrees	.042 degrees
EL			
Bias	.050 degrees	.050 degrees	.050 degrees
Random	.058 degrees	.035 degrees	.035 degrees
Total	.077 degrees	.061 degrees	.061 degrees

* Random error negligible compared to bias

The accuracy requirements for RNAV are shown in Table D.2. These values are indicative of the minimum acceptable error tolerances for an RNAV system. In general, most RNAV installations derive position information with greater precision than indicated by the minimum requirements of AC90-45A [10]. Flight tests of several representative RNAV systems demonstrated this fact. The results of these experiments, performed in support of a study of flight technical error (Reference 31), are shown in Figure D.3. These statistics were derived from an ensemble analysis of a series of tests conducted at NAFEC and at the Miami and Denver terminal areas and thus this data might be more representative of the errors incurred prior to MLS signal reception. The subject of RNAV/MLS transition is a significant aspect of the MLS system impact analysis and this consideration is the principal subject of discussion in Section D.2.

Although the RNAV and MLS computations display similar characteristics the exact method of route following may differ. RNAV routes are generally specified as great circle segments between station-referenced (range and bearing relative to station) or geographic referenced (latitude and longitude) waypoints. The precise nature of MLS route definition has not been specified. Route definition may consist of similar RNAV waypoint specifications or as curved arcs between waypoints. Furthermore, the MLS measurements are runway referenced. Section D.3 presents a more detailed discussion of the potential route following differences.

As discussed previously, a high degree of commonality exists between the computational requirements of RNAV and MLS. In the interest of minimum cost avionics it is highly desirable to combine as much of the onboard software and electronics as possible. This can be achieved through proper preprocessing of MLS and RNAV measurements to transform the measurements into a common coordinate system. The subsequent guidance computations can then be performed by a common set of software algorithms. The computational compatibility is discussed in detail in Section D.4.

In like manner it is highly desirable to have commonality in the displays for RNAV and MLS. Both of these sytems essentially display course deviation, hence it is feasible to have a common display shared by both rather than having redundant displays. A brief discussion is also presented in Section D.4 regarding display requirements.

A guidance scheme with the potential for handling air traffic in the dense terminal area of the future is 4D guidance. The additional control parameter is along track or time control. Though not necessarily required, this additional control capability can provide the basis for the application of metering and spacing concepts. Since 4D guidance is primarily useful for sequencing of aircraft (especially in the terminal area) a potential interface problem arises between 4D RNAV and 4D MLS. The fundamental aspects of 4D guidance constitute the third subject of discussion in Section D.4 where a comparison of RNAV and MLS 4D guidance is presented.

Although RNAV and MLS are intended to serve diverse functions, there are several areas in which the functional capabilities of RNAV might be used to complement the operational characteristics of MLS. These areas are identified and discussed further in Section D.5.

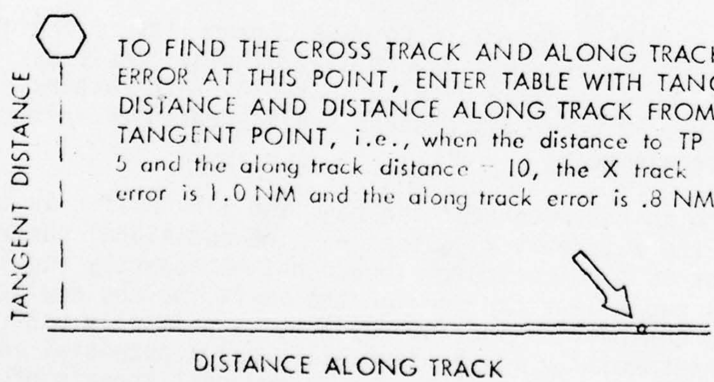
Table D.2

AC90-45A [10] RNAV Errors

FINAL AREA FIX DISPLACEMENT AREA (95% PROBABILITY)

DISTANCE ALONG TRACK FROM TANGENT POINT

DISTANCE FROM TANGENT POINT TO VORTAC	0	5	10	15	20	25	30
0 (x trk)		.8	.9	1.2	1.4	1.7	2.0
(alg trk)		.7	.7	.7	.8	.9	1.0
5 (x trk)	.9	.9	$\boxed{1.0}$	1.2	1.4	1.7	2.0
(alg trk)	.6	.7	$\boxed{.8}$	.8	.9	1.0	1.1
10 (x trk)	.9	.9	1.0	1.2	1.5	1.7	
(alg trk)	.8	.8	.9	.9	1.0	1.1	
15 (x trk)	.9	.9	1.1	1.3	1.5	1.8	
(alg trk)	1.1	1.1	1.1	1.2	1.2	1.3	
20 (x trk)	.9	1.0	1.1	1.3	1.6		
(alg trk)	1.3	1.4	1.4	1.4	1.5		
25 (x trk)	1.0	1.1	1.2	1.4			
(alg trk)	1.6	1.6	1.7	1.7			
30 (x trk)	1.2	1.2					
(alg trk)	1.9	1.9					



TO FIND THE CROSS TRACK AND ALONG TRACK ERROR AT THIS POINT, ENTER TABLE WITH TANGENT DISTANCE AND DISTANCE ALONG TRACK FROM TANGENT POINT, i.e., when the distance to TP = 5 and the along track distance = 10, the X track error is 1.0 NM and the along track error is .8 NM.

ERROR ELEMENTS

GROUND
- VOR 1.9°
- DME 0.1 NM

AIRBORNE
- VOR 3.0°
- DME 3% or 0.5 NM

RNAV SYSTEM 0.5 NM

PILOT
- CROSS-TRACK 0.5
- ALONG-TRACK ZERO

Table D.3 Terminal Area Flight Test Errors (1σ), Reference 31

System Type	General Aviation (Basic System)	Air Carrier (ρ/θ + Air Data)	Air Carrier (Multisensor)
Along Track Error (nm)			
Bias	.21	.03	.04
Random	.42	.26	.14
Total	.47	.26	.15
Cross Track Error (nm)			
Bias	.19	.12	.02
Random	.48	.30	.15
Total	.52	.32	.15

D.2 RNAV/MLS TRANSITION ERRORS

In the RNAV environment the achievable position accuracy due to navigation errors is highly geometry-dependent. The primary source of error is the VOR error which creates a range-dependent position error. Hence, the closer the aircraft is to the gound facility the smaller the position error. For most primary airports a VOR/DME facility is located in the proximity of the runways. Depending on the final approach geometry and MLS coverage pattern this may or may not be the most desirable location.

The geometry dependence is best illustrated by example using the error quantities of Table D.2. Consider the geometry in Figure D.2. A 90° turn to final is assumed for a flight path terminating at a 10,000 foot runway. The MLS transmitter is assumed to be located at the end of the runway, providing coverage within a sector 60° either side of the extended runway centerline. With a 7,500 foot turn radius the final approach path length is assumed to be 2.13 nm. Thus the tangent distance to a VOR/DME facility located at the end of the runway would be five nm from the descent path (the tangent distance of five nm corresponds to one of the rows in Table D.2). Assume three potential VOR/DME facility locations: (1) directly opposite the intersection of the flight path with the MLS boundary, (2) at the runway, and (3) six miles beyond the runway. The along-track distance to the RNAV/MLS intersection (point A) is 0 nm for facility 1, 9 nm for facility 2, and 15 nm for facility 3. Table D.4 shows the corresponding cross-track, along-track and vertical deviation for 3° and 6° glide slopes, respectively, at point A (RNAV delivery errors at the MLS boundary) due to VOR and DME errors for each of the three facilities. In Table D.2 the cross-track error values contain a 0.5 nm flight technical error. Table D.4 shows the cross-track error with and without the flight technical error component for comparison purposes. The vertical deviation arises from the propagation of the along-track deviation into the vertical channel which is characteristic of 3D RNAV systems. For comparison, the vertical deviation is presented for CTOL (3°) and STOL (6°) type descent paths.

Table D.4

Position Errors Due to VOR/DME Errors for Three Facility Locations

Facility*	Cross-Track (with FTE) nm	Cross-Track (No FTE) nm	Along-Track nm	Vert.Dev. CTOL (3°) Feet	Vert.Dev. STOL (6°) Feet
1	0.90	0.75	0.60	191	382
2	0.98	0.84	0.78	249	498
3	1.20	1.09	0.80	255	510

* These refer to facility locations illustrated on Figure D.2

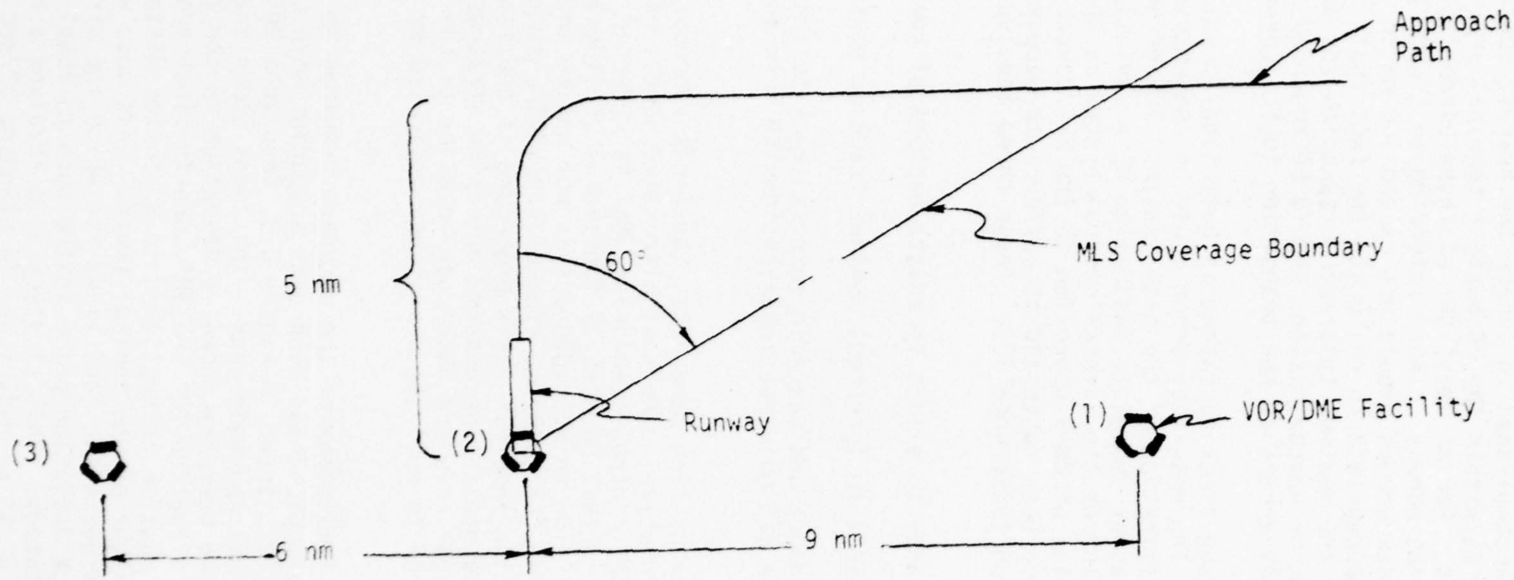


Figure D.2 Three Hypothetical VOR/DME Facility Locations for Evaluation of RNAV Delivery Errors

To establish a basis for examining the issue involving RNAV/MLS transition maneuvers, a survey was accomplished to locate the nearest VORTAC station relative to the 23 airports within the 20 busiest terminal areas of the continental United States. For at least 80% of these airports, a VORTAC was located within 10 nm of the runway. Thus, referring to Figure D.2, both the cross track and along track errors should not exceed 1.0 nm in a majority of cases. Again it is appropriate to reiterate the fact that these error specifications represent the maximum tolerable accuracies for an RNAV system and thus the resulting error approximations should be regarded as conservative estimates of expected RNAV errors at the transition to MLS coverage.

The impact of an along track deviation is only significant when time control is implemented. The resulting error could be compensated by a speed reduction or a modification of the path length. The effect of a cross track error is realized as an immediate indication of a deviation from the intended track to the pilot or the lateral control system as the aircraft transitions from the region of RNAV operation to the MLS coverage sector. At least three stategies have been suggested as appropriate maneuver sequences to null out this deviation (Reference 33). These three involve the following procedures:

- Utilize MLS guidance to effect immediate capture of nominal track
- Utilize MLS guidance to intercept nominal track at next waypoint
- Utilize RNAV guidance and maintain current track to intercept next segment. Utilize MLS guidance in executing the turn to following track.

Of the three suggested transition maneuvers, the first procedure is probably the most acceptable alternative. The most attractive aspect of this procedure is the fact that, from the control standpoint, MLS is regarded as just another navigation signal input in that no special functional considerations are accorded MLS. The transition to MLS coverage is not unlike the transition during RNAV operation from the coverage area of one VORTAC station to another. A significant consideration involving this procedure is the limitation on airspace available to execute the necessary correction strategy. Another consideration is the flight crew and passenger reaction to the possibly abrupt maneuver sequence required to null the deviations indicated by the MLS navigation data.

To investigate the limitation on the airspace required to execute the transition maneuver, two typical approach path scenarios were considered. The two approach geometries, shown in Figure D.3, involve a 90° and a 180° turn to intercept the final approach path. The turns shown are defined by 1 nm radius arcs. For the geometry shown, a deviation to the left of track represents a worst case situation for the 90° turn-to-final procedure since the corrective maneuver must be accomplished in a shorter distance than that for a deviation to the right of the nominal track. This case was examined further to determine the geometric conditions for which the aircraft could eliminate the cross track deviation prior to the turn to final by executing a 30° track intercept stategy. This strategy also involves a roll-in and roll-out maneuver along a .85 nm radius arc (a standard 3°/sec turn at 160 kt).

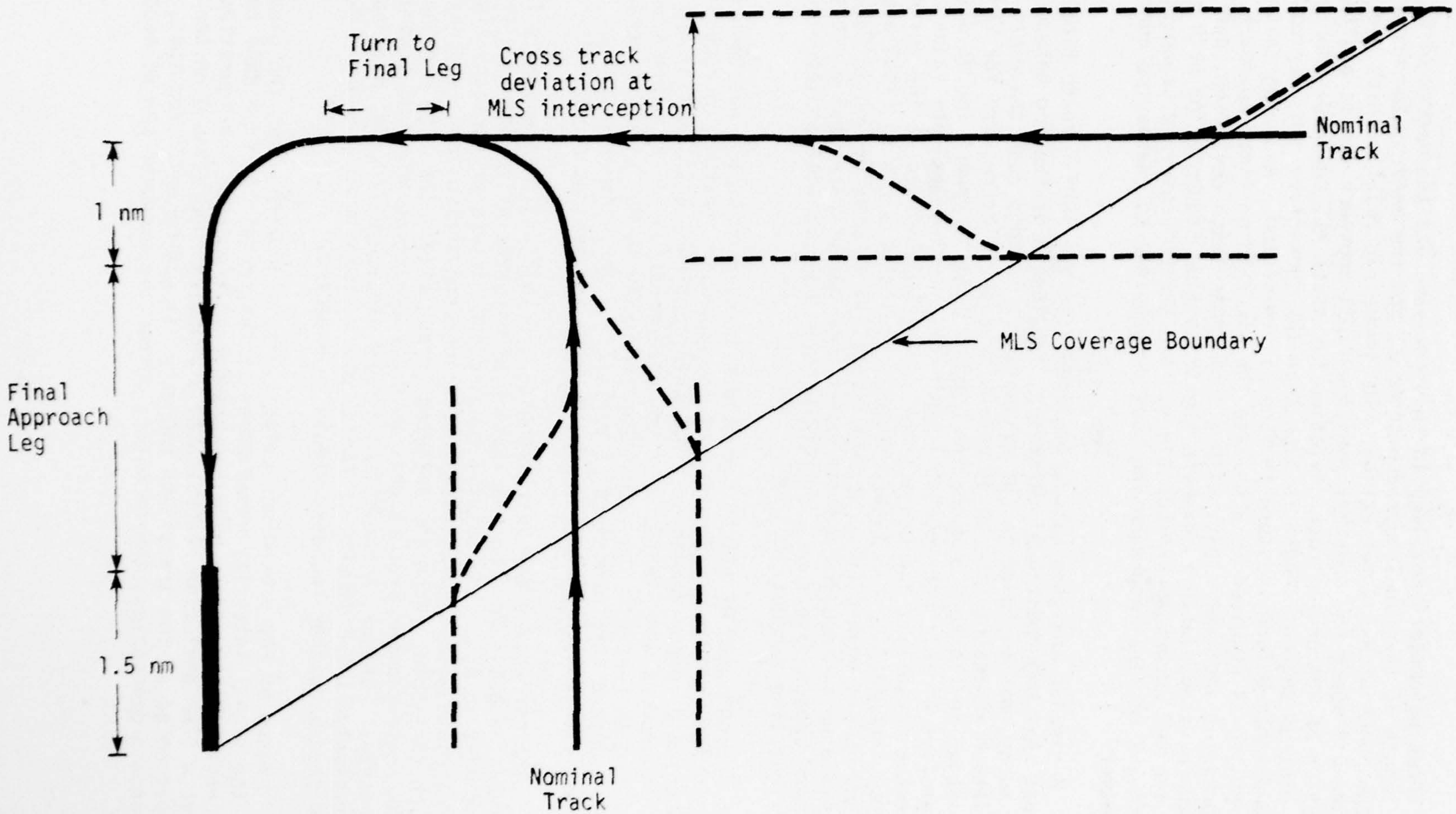


Figure D.3 Track Geometry for RNAV/MLS Transition

The three parameters involved in this analysis are the degree of MLS coverage, the length of the final approach segment, and the RNAV system error observed at the point of MLS interception. The geometric relationships are shown in Figure D.4 where the shortest possible final approach leg is plotted as a function of the cross track deviation for three MLS coverage configurations. The minimum segment length is such that the corrective maneuver could be accomplished before the turn to final is initiated. Assuming that at least a 3 nm leg is required to stabilize the aircraft on final approach, this information indicates that, with a 1 nm cross track deviation, sufficient airspace is available to execute the transition sequence for both the 40° and the 60° coverage configurations. For the 20° coverage capability, at least a 7 nm final approach leg must be provided to enable the corrective maneuver.

A similar analysis was accomplished for the 180° turn-to-final procedure except that one additional parameter, the length of the leg between consecutive 90° turns, was included in the evaluation. In this case the right of track deviation represents the worst case situation. The results for this case are shown in Figure D.5 where the minimum final approach leg is displayed as a function of the turn segment length for selected discrete values of MLS coverage capability and cross track deviation observed at the point of MLS signal reception. This figure demonstrates that a 2.5 nm final approach leg is sufficient when a 60° coverage capability is provided while for the 40° case 4.5 nm is required. The results also demonstrate that a continuous turn is more appropriate than a segmented turn sequence with an intermediate straight line segment.

The question of flight crew and passenger reactions has been tacitly considered in the specification of the maneuver strategy to accomplish the reduction of error incurred at MLS interception. Both initial and final 3°/sec turn maneuvers were factored in the determination of the along track distance required to complete the transition from RNAV to MLS signal coverage. Since this standard turn procedure is currently a very common practice, it is unlikely that such a strategy would raise any serious objections.

The correction maneuver suggested in this analysis was only intended to serve as a basis for the examination of airspace utilization in the transition from RNAV to MLS. The initial turn and 30° intercept strategy might only be appropriate when the indicated deviation from the nominal track exceeds a given threshold. When the detected error is less than the threshold, then a bank angle command proportional to track deviation would be a more appropriate strategy. Further, since MLS is a more precise navigation data source, relatively little damping of the signal in the control law would be required and thus a quicker response should be expected.

Based on the preceding analysis, it is apparent that the discontinuity in the signal integrity experienced at the transition from RNAV to MLS can be easily accommodated with the broader coverage MLS configurations. Assuming that a 1 nm deviation respresented a practical upper bound on the discontinuity experienced at the transition boundary, it was demonstrated that, for typical approach geometries, the necessary corrective maneuver can be accomplished

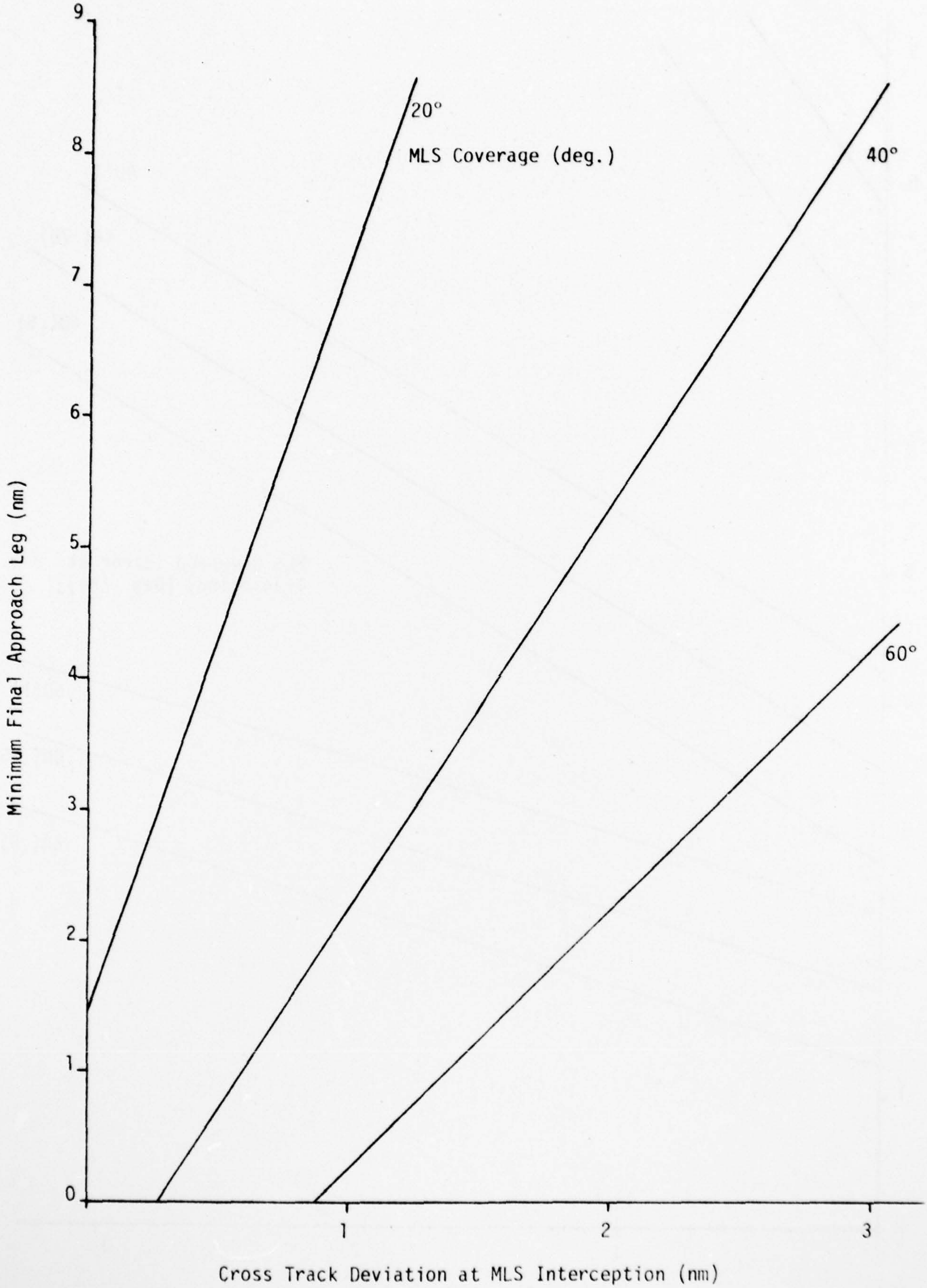


Figure D.4 Minimum Final Approach Leg For 90° Turn-to-Final

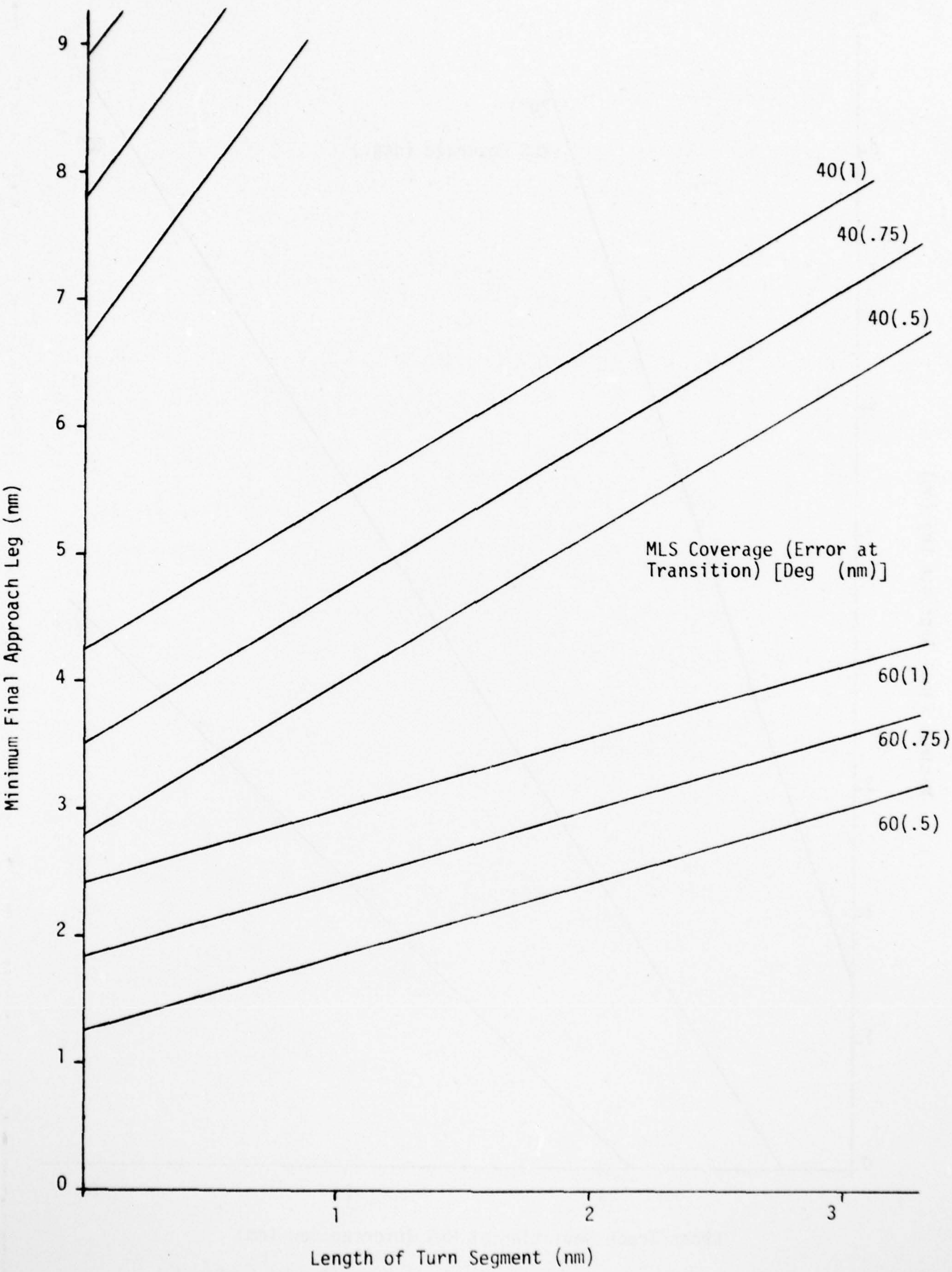


Figure D.5 Minimum Final Approach Leg for 180° Turn-to-Final

within the available airspace. With a 60° MLS coverage capability, a 3 nm final approach leg for either a 90° or 180° turn-to-final approach profile affords ample time to accomplish the required transition maneuver prior to the turn. As the angular extent of MLS coverage decreases, the minimum distance final approach leg increases to allow sufficient space in which to accomplish the transition strategy. With 20° MLS coverage, a close-in interception of the MLS signal is practically impossible when a 1 nm discontinuity is assumed. In this case it might be well to consider an alternative transition maneuver such as the previously mentioned strategy where the capture of the MLS-defined track is achieved at the next waypoint. Also, the previous discussion relates to the situation where it was required that the MLS-defined track be intercepted in advance of the turn to the final approach leg. If only the narrow beam MLS coverage were available, then it would be appropriate to consider a transition strategy similar to the ILS capture procedures in current practice.

Unlike the lateral case, the consideration of appropriate maneuver strategies to accomplish the vertical transition presents a very confusing dilemma. There are two principal causal factors contributing to this confusion. First, it is impractical to consider an immediate correction to the MLS-defined flight level since a "fly-up" maneuver in response to a low altitude indication would be inefficient in view of the fact that in level flight the aircraft will eventually intercept the desired vertical flight path along the nominal descent gradient. The second and perhaps more significant issue involves the assumptions inherent in the association of pressure with altitude. Aircraft within the same column of air are all subject to the same error due to a non-standard temperature lapse rate. Likewise, aircraft at different altitudes above a given geographic area all experience the same variations in indicated altitude due to deviations of the local pressure from the broadcast reference. Thus it is assumed that pressure-altitude is a valid indicator of the vertical separation between two similarly equipped aircraft since the indicated pressure differential between aircraft is relatively insensitive to local variations in pressure-related factors. However, the errors attributed to non-standard lapse rates and horizontal pressure gradients strongly influence the interpretation of pressure as indicative of the height above the local terrain. Similarly, when an aircraft sensing altitude derived from MLS range and elevation is introduced, the same factors contribute to a false indication of vertical separation between the MLS-equipped aircraft and the aircraft equipped with a barometric altimeter. Thus the separation standards must be increased accordingly to accommodate the variety of aircraft altitude sensors. The net effect is best demonstrated with reference to the respective error budgets shown in Table D.5 for the two system environments: a uniform environment of all barometric altimeter equipped aircraft and a mixed environment with both barometric and MLS-derived altimeter systems. The 3σ errors shown were obtained from Reference 11 assuming an altitude of 10,000 ft. and an MLS range of 20 nm. For the uniform environment the errors attributed to lapse rate and pressure gradient effects do not contribute to the minimum vertical separation since, as previously indicated, all aircraft experience these effects to the same degree. In the case of the mixed environment, these error effects are significant and thus influence the determination of the minimum vertical separation. The VNAV

Table D.5 3σ Error Budget (ft.) - 10,000 ft.

Error Effect	Uniform Environment	Mixed Environment	
	Baro	Baro	MLS
Instrument	150	150	
Lapse Rate		300	
Pressure Gradient		800	
MLS Elevation			388
VNAV	150	150	
FTE	250	250	250
Vertical Separation	956	1750	

equipment and flight technical error values specified for the barometeric altimeter configuration are those suggested in the RTCA committee report on the minimum operational requirements for VNAV equipment (Reference 10). For the MLS-equipped aircraft it is assumed that the VNAV equipment error is negligible since the implementation of MLS would require a digital capability. Thus the VNAV error primarily attributed to the coarse computational ability of an analog system would be diminished. The minimum vertical separation requirements were determined by

$$6\sigma/\sqrt{2} + 300$$

where σ is the RSS combination of the errors assumed for two vertically adjacent aircraft. As shown in Table D.5 the required separation increases dramatically when an aircraft sensing altitude without reference to barometric pressure is introduced in the uniform baro-altimeter environment (This conflict with MLS is not peculiar to the RNAV environment but would exist in any situation where the indicated altitude is pressure derived, i.e. the terminal area where radar vectors and designated flight levels are provided).

The increased separation requirements due to the inclusion of MLS in the pressure-altitude environment would discourage the use of an immediate transition strategy to MLS-defined altitude at the coverage boundary. If the immediate transition strategy were adopted, then the current separation requirement of 1000 ft. would have to be increased to 2000 ft. to accommodate the mix of altitude sensing instruments. However, since the lapse rate and pressure gradient errors are inversely proportional to sensed pressure, it would be advisable to delay the transition to the MLS vertical reference until the lower altitudes where the errors have a less significant effect on the required separation standards. This strategy should not have a severe impact on the objectives of terminal area control concepts. Unlike the lateral case where precise path control is a requirement for effective metering and spacing, the accurate determination of aircraft height above ground level is only a critical factor during the final approach phase. Outside the terminal area vertical separation assurance is the dominant consideration.

To demonstrate the effect of altitude on the minimum separation requirements, consider the error budget shown in Table D.6 in which the errors encountered at 4000 ft. are displayed. In addition to reducing the lapse rate and pressure gradient errors, the decreased altitude also results in lower suggested values for the VNAV equipment and flight technical errors (Reference 10). The resulting minimum vertical separation indicates that

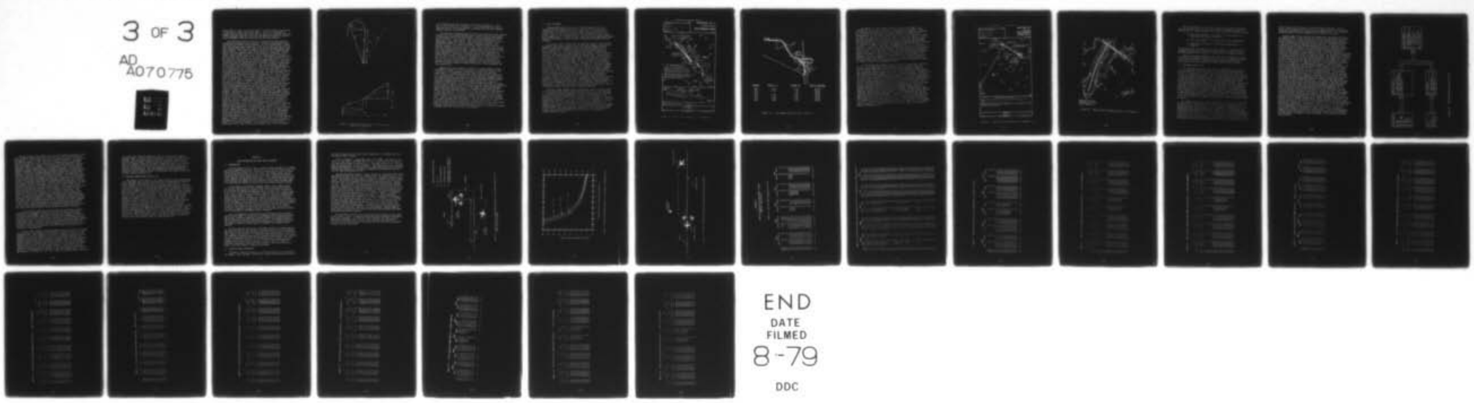
Table D.6 3σ Error Budget (Ft.) - 4,000 Ft.

Error Effect	Baro	MLS
Instrument	150	
Lapse Rate	120	
Pressure Gradient	320	
MLS Elevation		223
VNAV	100	
FTE	150	150
Vertical Separation	998	

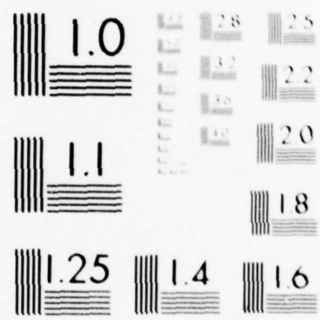
AD-A070 775 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
SYSTEMS INTEGRATION: RNAV AND THE UPGRADED THIRD GENERATION SYS--ETC(U)
DEC 76 E H BOLZ, R W SCOTT, A R STEPHENSEN DOT-FA72WA-3098

UNCLASSIFIED FAA-RD-77-22 NL

3 OF 3
AD
A070775



END
DATE
FILMED
8-79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

below 4,000 ft. (AGL), the current 1,000 ft. standard would be appropriate for the mixed altitude sensor environment. Thus, it is reasonable to suggest that the transition to MLS vertical guidance be postponed until the aircraft descends below this level and that above this level all aircraft rely on barometric pressure indications for altitude reference.

Two alternative vertical transition strategies were considered as appropriate to accomplish this objective. The first alternative involves a transition to the MLS vertical reference as the aircraft enters a sector about the extended runway centerline. This sector might coincide with the final approach maneuvering area proposed as part of the RNAV terminal area design concept. This area is defined as the sector 22 1/2 degrees either side of the final approach course to the runway in current use. This 45 degree sector extends 15 to 30 nm from the airport location while the limit on the vertical extent of this area is established in accordance with the particular requirements of a given area. The identification of this MLS transition zone with the final approach maneuvering area is particularly convenient since the maneuvering area is intended to serve as a dedicated region within which approaching aircraft are free to maneuver without fear of any conflict with crossing traffic. Thus any limitations imposed by the increased separation standards in a mixed sensor environment would be of no consequence since crossing routes are already prohibited by the requirements of the terminal maneuvering area. The only provision required to guarantee adequate vertical separation would be the establishment of a suitable buffer zone above the terminal maneuvering area. If the vertical dimension of this area were limited to 4,000 ft. then a 1,000 ft. buffer would be appropriate. If the vertical extent were greater than 4,000 ft., then a 2,000 ft. buffer zone would be required since separation standards are usually quantized in 1,000 ft. increments. Another consideration related to the identification of the MLS vertical transition zone with the final approach maneuvering area involves the availability of sufficient airspace in which to accomplish the corrective action required. The significant factor in this respect is the expected error at the transition boundary. Based on the error statistics specified earlier, upper bounds of 200 ft. and 300 ft. were estimated for the MLS and barometric altimeter systems, respectively. Thus a 400 ft. error was considered representative of the worst case error to be expected at the transition to MLS vertical guidance. Also, an extremely demanding approach path was formulated to examine the vertical maneuvering requirements. The test case shown in Figure D.6 involves a 3 nm final approach segment with a preceding 180 degree turn-to-final along a 1 nm arc segment. The transition to the final approach maneuvering area occurs along the turn segment 2.9 nm distant from the final approach fix. Assuming that the aircraft must be stabilized on the 3 degree final approach gradient requires that a 4.5 degree glide-slope be maintained to remove a 400 ft. positive deviation. Undoubtedly this corrective action would stimulate harsh criticism from the airline fraternity; however, it should be recognized that the required maneuver is not impossible and very likely less improbable than a 3 nm final approach segment. Further, the resulting vertical flight path is not unlike the two-segment noise abatement approaches which have been executed without the benefit of MLS vertical guidance. For the negative altitude error at transition, level flight along the turn segment leads to the interception

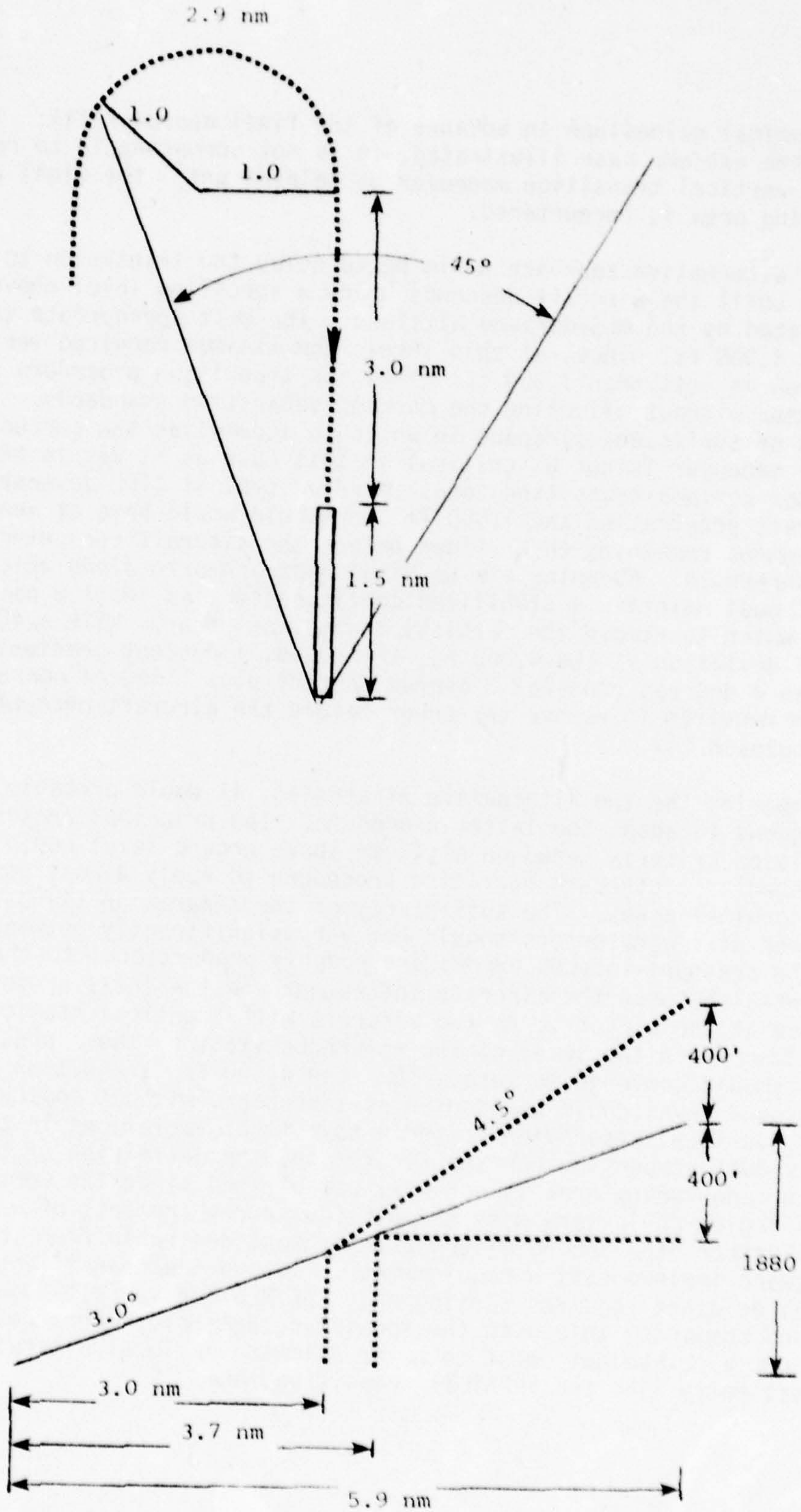


Figure D.6 Maneuvering Requirements for Transition to MLS Vertical Guidance

of the nominal glideslope in advance of the final approach fix. Thus, even in the extreme case illustrated, it is not unreasonable to require that the vertical transition maneuver be delayed until the final approach maneuvering area is encountered.

The alternative approach would be to delay the transition to MLS vertical guidance until the aircraft descends below a specified level above ground as indicated by the MLS-derived altitude. The most appropriate threshold would be 4,000 ft. since, at this level, the minimum required vertical separation is less than 1,000 ft. Thus the transition procedure could be implemented without affecting the current separation standards. The question of sufficient airspace in which to accomplish the corrective vertical maneuver is not as critical in this case as it was in the case of the sector defined transition zone. Given a typical CTOL descent gradient, an aircraft penetrating the 4,000 ft. threshold would have at least a 12 nm track segment remaining to be flown before the aircraft encounters the runway threshold. Assuming a 6 nm final approach path along which the aircraft must maintain a stabilized configuration, at least 6 nm are available in which to remove the vertical transition error. With a 400 ft. vertical deviation at the 4,000 ft. threshold, a descent gradient of no more than 4 degrees (nominal 3 degree descent plus 1 degree correction) should be required to remove the error before the aircraft encountered the final approach fix.

Comparing the two alternative strategies, it would probably be more advantageous to adapt the latter procedure. The principal reason is that a transition criteria based on altitude above ground level could be established as a standard operating procedure to apply almost universally to all terminal areas. The sufficiency of the separation standards based on assumed altimetry errors should not vary significantly between locations since the pressure-induced errors are roughly proportional to the height differential between the aircraft instrument and the local pressure reference at the airport. As two aircraft with identical static instrument errors descend to the level of the reference station, these pressure sensitive factors should converge to zero. Thus the 4,000 ft. transition threshold above ground level could be adopted as a standard without modifying the 1000 ft. vertical separation criteria to reflect variations in the elevation of individual airports. For the first case, the definition of the final approach maneuvering area is not well established since the vertical extent of this region could vary with the particular requirements of each terminal area. Further, the second alternative is most desirable from the standpoint of software implementation requirements. To cue the transition to MLS vertical guidance requires sensing only the MLS-derived altitude above ground level and comparing this with the specified threshold. For the first technique, a determination of both the azimuth and local altitude are required to detect entry into the vertical transition zone.

D.3 ROUTE FOLLOWING

Although RNAV and MLS are usually considered mutually exclusive navigation concepts appropriate to the enroute and terminal area phases, respectively, it should be realized that RNAV could be applied to the terminal area to gain some of the operational advantages expected of MLS either in advance of MLS implementation or in lieu of MLS at airports where MLS implementation is a distant reality. These operational advantages include reduced noise exposure, increased runway utilization and improved obstacle avoidance.

A classical example illustrating the potential benefits of MLS guidance for lateral path control involves the current visual approach procedure to runway 18 at Washington National (Figure D.6) and the consideration of MLS in extending this procedure to apply to conditions when instrument flight rules prevail. Primarily intended as an obstacle clearance and security measure, the DCA visual procedure also serves to minimize the noise impact by concentrating the noise over the Potomac River. The procedure is definitely a visual approach, applicable whenever the ceiling is at least 3500 feet and visibility is at least 3 miles. The approach is initiated after direction is provided by radar vectors to a point 10 nm northwest of the terminal at an altitude of 3,000 ft., whereupon the aircraft proceeds to visually follow the river to a landing on runway 18. The nominal ground track could be approximated as a sequence of straight-line and arc segments (Figure D.7) so that, with appropriate modifications, an autopilot/guidance system driven by MLS-derived navigation data could execute the procedure without reference to visually acquired ground features. The benefits derived from the implementation of this MLS procedure relate to the increased utilization under IFR conditions of this relatively noise insensitive procedure, and also to the increased utilization of runway 18, now critically hindered by insufficient landing aids. Unfortunately, due to the unique security restrictions about the Federal Office complex, landing guidance can only be provided when the visibility and ceiling exceed 1 nm and 720 ft., respectively. Thus, this particularly complex curved approach could result in a substantial benefit to operations at Washington National.

Although an RNAV computer could be configured to permit guidance along a curved approach path such as the previously indicated DCA River approach, it is doubtful that when implemented the system could provide the necessary precision dictated by the requirements for that curved procedure. For example, in the case of the DCA River approach, the system must demonstrate an accuracy on the order of .1 nm in accordance with the nominal width of the Potomac River corridor. Should the aircraft deviate significantly from the course of the river, then the conditions established to minimize noise exposure are violated. Thus if there exists a requirement for such a complex curved approach there must also exist a requirement for a precision landing aid such as MLS, since the conditions dictating the need for such precise control over the achieved ground track can only be satisfied with an accurate navigation source.

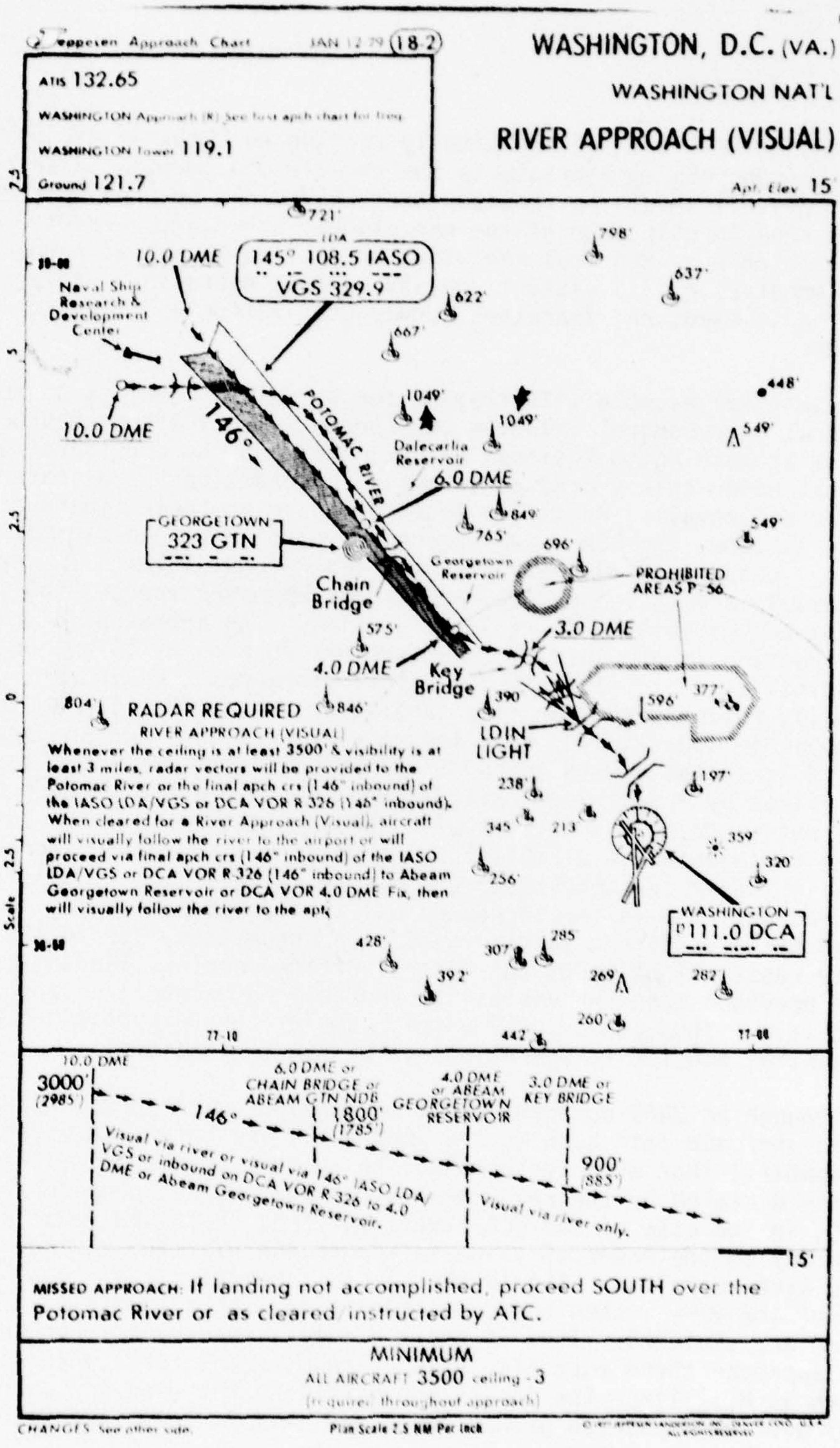
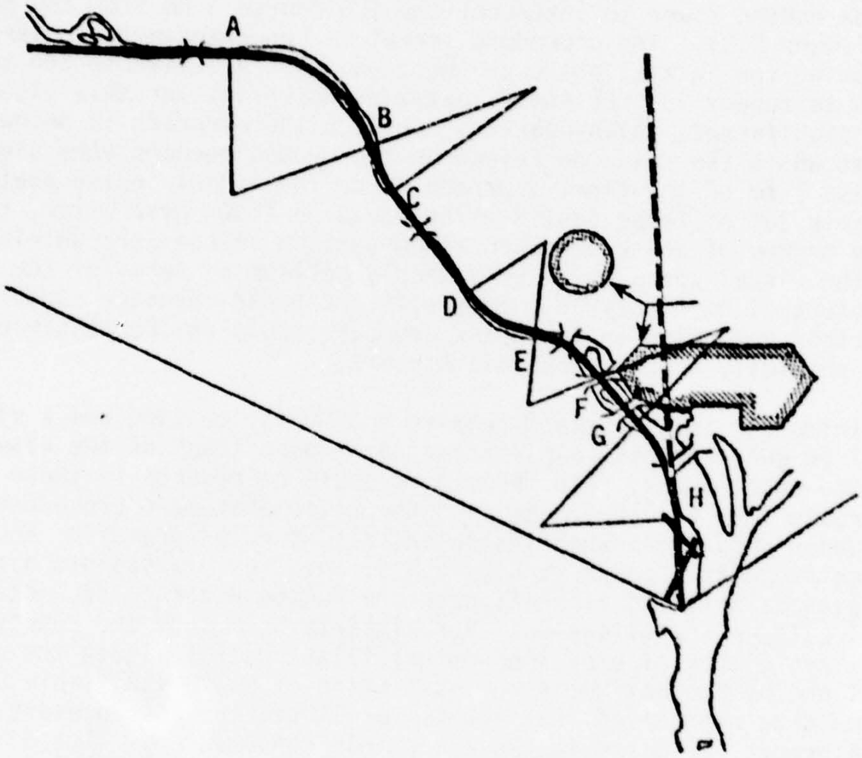


Figure D.6 Visual River Approach to DCA - Runway 18



Segment	Radius, nm	Length, nm	Time at 120 Knots
A-B	1.95	2.09	62.74
B-C	2.27	.74	22.06
C-D		1.72	51.68
D-E	1.23	0.98	29.42
E-F	1.04	1.03	30.83
F-G	1.96	0.82	24.72
G-H	1.89	1.40	41.85

Figure D.7 Arc Segment Approach to DCA - Runway 18

One should not infer from the previous discussion that RNAV is an inappropriate concept in the context of curved approach procedures. There are indeed several examples illustrating the potential for RNAV as an approach aid to achieve the operational advantages commonly associated with MLS implementation. As an example, consider the current visual approach procedure to runway 13 at New York's LaGuardia Airport. The procedure involves a flight path over the Hudson River to intercept the ILS course 5 nm from the runway threshold (Figure D.8). The procedure serves to concentrate the noise over the river during the initial phase of the approach. Relative to the straight-in ILS approach to runway 13, the noise abatement potential for this visual approach is significant. Along the ILS approach the aircraft is below 2000 ft. (the level at which the noise perceived on the ground becomes very significant) along the last 7 nm of the final approach. For the visual (noise abatement) approach nearly 30% of these last 7 miles would be flown over water, therefore reducing the degree of noise exposure in comparison to the straight-in ILS approach. The visual approach is very nearly optimum in terms of the noise abatement potential on runway 18. Even with the broad coverage capabity of MLS, any further reduction in the noise exposure would not be possible because of Harlem's proximity to the LaGuardia Airport.

The minima for this approach require a 3200 ft. ceiling and a visibility of 5 nm. If an RNAV approach duplicating the ground track of the visual procedure were established, then the minima could be reduced to those for the ILS approach (200 ft. and .5 nm) and the noise abatement procedure would thus apply under conditions when instrument flight rules prevail. An appropriate RNAV approach procedure, shown in Figure D.9, involves 3 waypoints directing the flight path of arriving aircraft over the Hudson River to the interception of the ILS localizer and glideslope approximately 5 nm from the runway threshold. The broken lines either side of the nominal flight path indicate the approach corridor defined by the maximum error statistics of AC 90-45A (Table D.2). Again it should be emphasized that the AC 90-45A statistics represent an upper bound on the errors permitted for an acceptable RNAV system. Thus it is expected that most aircraft will maintain the nominal flight path with a greater precision than that indicated by the approach corridor bounds. Most commercial carriers should not be expected to deviate from the nominal track by more than .30 nm and thus should maintain a flight path within the corridor above the course of the Hudson River. Further, it should be noted that the approach corridor defining the lateral deviation from track of the worst-case RNAV system avoids the structural obstacles of midtown and lower Manhattan, particularly the World Trade Center at 1749 ft. and the Empire State Building at 1521 ft. Thus the suggested RNAV approach to LGA runway 13 could be applied well in advance of MLS implementation to realize the same noise abatement potential expected for MLS.

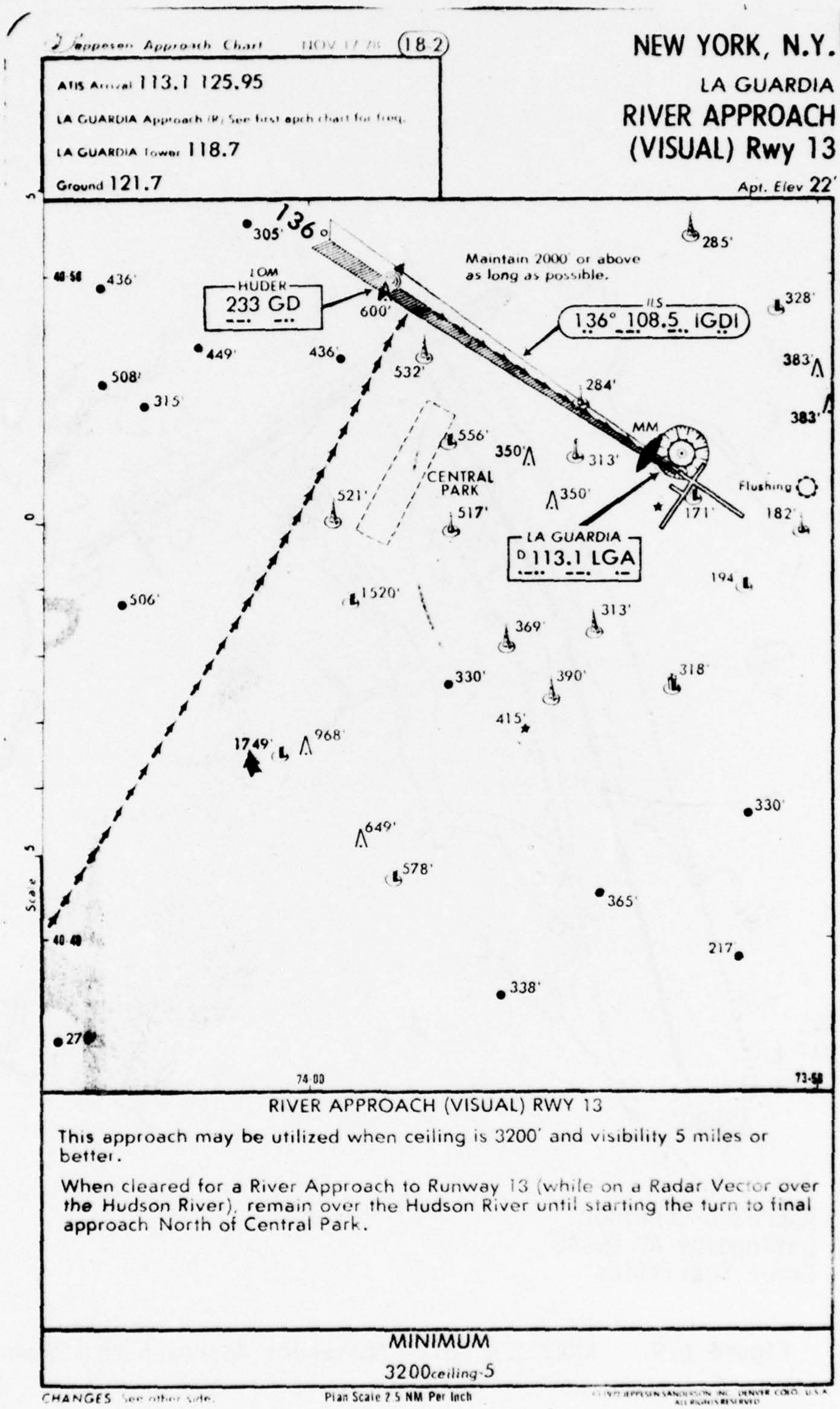


Figure D.8 Hudson River Visual Approach to LGA-Runway 13

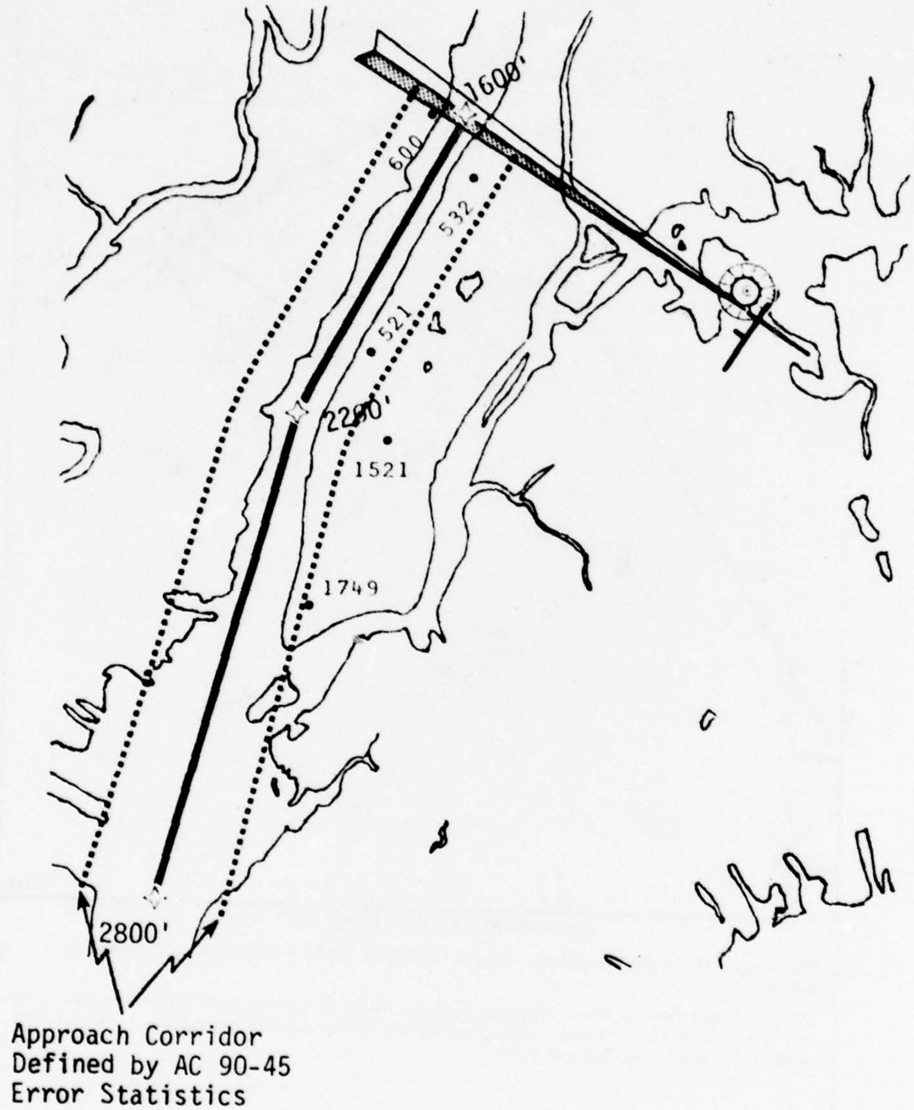


Figure D.9 RNAV IFR Noise Abatement Approach to LGA Runway 13

The visual approach to LGA runway 13 over the Hudson River represents only one of several current visual noise abatement procedures suitable for RNAV adaptation. Other approaches identified as potential candidates include:

- The visual approach to LGA runway 31 over the Long Island Expressway and Flushing Meadow Park.
- The visual approach to PHL runway 9R over the Delaware River
- The Canarsie LDIN (lead-in light system) approach to JFK runway 13L

In the latter case, the short, curved final approach leg achieved with the system of lead-in lights to intercept the ILS course may not be feasible with RNAV, particularly since the ILS course itself is so short (2 miles).

The noise abatement problems at many other airports could be relieved through the use of RNAV to intercept the ILS course. The RNAV routes would be designed to overfly the least noise-sensitive area, with altitude restrictions set to avoid obstacles, and then intercept the ILS course.

D.4 FUNCTIONAL COMPATIBILITY

Too often RNAV and MLS are interpreted as independent and sometimes competing functional objectives within the framework of the Upgraded Third Generation ATC system goals. This unfortunate disassociation of the two programs is probably due in part to the fact that RNAV and MLS are identified as separate program objectives of UG3RD. Basically, RNAV is an operationally-oriented objective providing the basis for a more flexible point-to-point navigation capability than that available with current procedures where flight paths coincide with VOR radials. On the other hand, MLS is principally a hardware-oriented program providing the signal source to enable guidance along more flexible approach paths than the current straight-in approaches coincident with the ILS localizer and glideslope beams. Thus the point-to-point navigation concepts afforded by RNAV are essential to the MLS concept. In fact, MLS could be considered as a sub-category of RNAV in the same sense as RNAV systems are classified according to the nature of the signal source, i.e., VOR/DME, DME/DME, inertial, LORAN, OMEGA, etc. In light of this interpretation it should not be surprising that the two subjects share common areas of concern.

One common factor is the subject of path specification. RNAV routes are defined in terms of waypoints and straight-line segments (great-circle arcs) connecting points. Without question the same general notation would be appropriate to MLS-defined approach paths. However, the degree of precision and the wide-area coverage by MLS in the terminal area has introduced the additional requirement for a parametric description of curved approach paths. As demonstrated in the case of the visual River approach to Washington National, flight paths combining both linear and arc segments are reasonably sufficient to approximate any curved approach. Thus to specify a curved approach it is only necessary to expand the RNAV waypoint concept to include the provision for

specifying the radius of the arc and the direction of the turn. This is easily accomplished by defining an additional waypoint indicating the center of the arc or alternatively by specifying, through waypoints, the inbound and outbound tangents to the arc together with the radius of curvature.

Another common factor involves the computational requirements shared by both RNAV and MLS. In both concepts the control functions performed by either the autopilot or the flight crew require that the computer output identical guidance parameters indicating the lateral, vertical, and heading deviations of the aircraft from the nominal path characteristics. Thus the guidance computations performed by the RNAV computer could also be applied to derive track deviations in support of the MLS guidance function. The RNAV guidance equations would apply directly to the MLS situation provided the format of the MLS navigation data is in a compatible form. The tasks performed in support of the guidance function involve (Figure D.10): the storage and retrieval of standard instrument arrival and departure routes, the sequencing of waypoints in accordance with the aircraft's achieved progress, the reconstruction of the nominal flight profile from the specified waypoints, the computation of aircraft deviations from the nominal path characteristics and the guidance to execute a turn in anticipation of a segment transition, or to achieve precise control along an arc segment of a curved approach procedure. The data storage capability provided with many airline-grade RNAV systems is applicable to the MLS subsystem and should be highlighted. The availability of such a memory capacity would significantly simplify the design and hence reduce the cost of providing the MLS function by using the RNAV processor. For the general RNAV/MLS system shown in Figure D.10, the navigation functions for each must necessarily be identified as separate subsystems since, in general, the RNAV processing requirements are dependent on the type of system involved and thus common RNAV and MLS computational components cannot be identified without reference to a specfic RNAV configuration. For example, when DME slant range and barometric altitute are both available and combined in the RNAV computer to derive horizontal range, then the same computational elements could be shared with the MLS navigation subsystem with altitude determined by MLS range, elevations, and the reported elevation of the transmitter site. In fact this approach might be very desirable in view of the previous comments regarding the non-simultaneous transition to lateral and vertical MLS guidance to satisfy vertical separation requirements. On the other hand, if the RNAV system derived position coordinates from inertial measurements, then it is doubtful that any commonality would exist between the RNAV and MLS navigation equations, since the RNAV subsystem would involve a dynamic integration of the aircraft equations of motion while the MLS subsystem involves a static transformation of coordinates. In total, the dominant factor in the consideration of RNAV and MLS computational requirements is the fact that a significant portion of the computational burden can be shared by both concepts. In fact, MLS could be considered as a supplemental sensor augmenting the navigation capabilities of RNAV in the terminal approach phase. Thus the implementation of RNAV with due consideration of MLS requirements would ease the transition from the current ILS approach control environment to the projected Microwave Landing System.

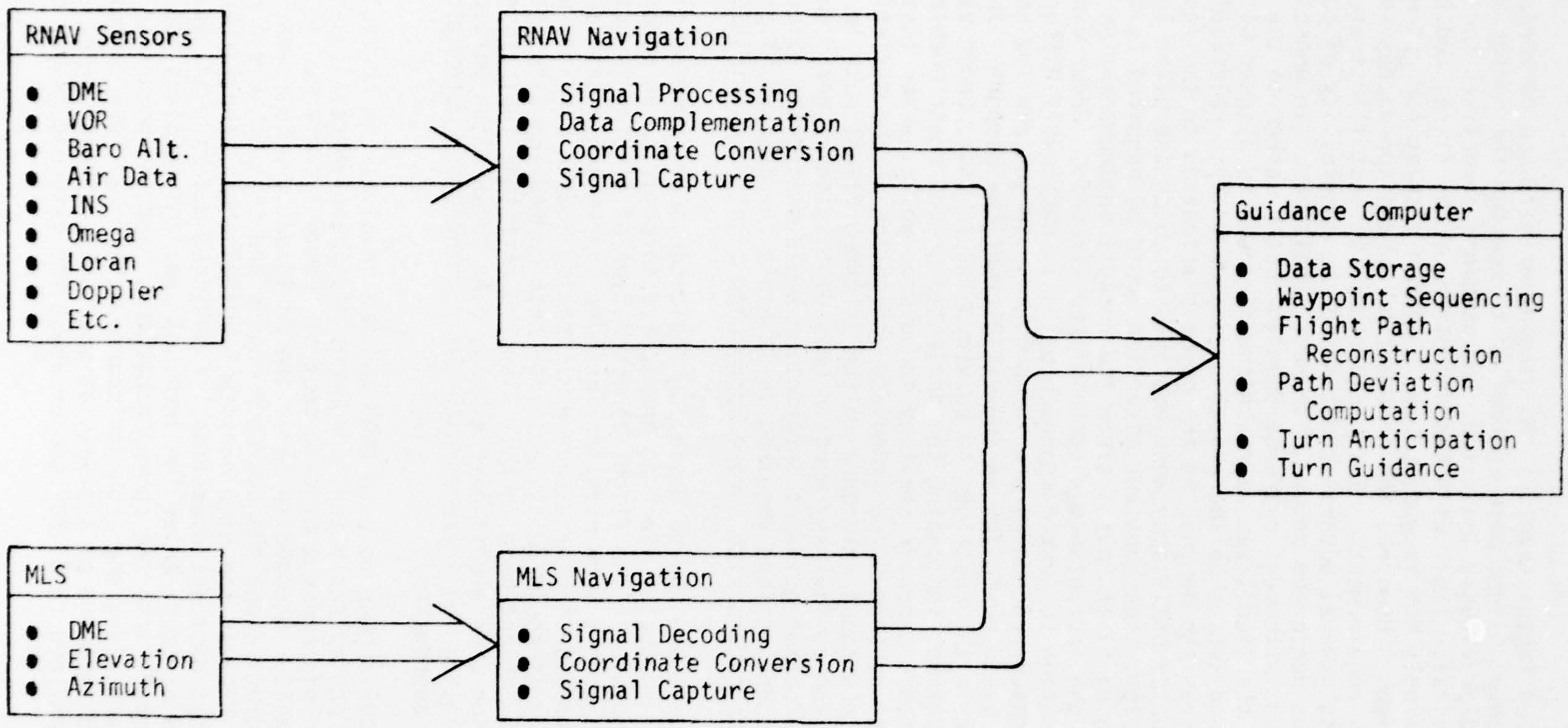


Figure D.10 RNAV/MLS Guidance System Functions

Another related factor involves the display of guidance parameters to the pilot to enable manual flight path control or to monitor the performance of the autopilot. As previously indicated, the guidance objectives for both MLS and RNAV are identical. Thus, with the exception of the flare, touchdown, and roll-out where only MLS is applicable, a common display concept would serve both objectives. However, the prospect of curved approaches suggests additional display requirements. This requirement is best illustrated with reference to pilots' general adverse reaction to the possibility of curved approach procedures performed under instrument conditions. In general pilots prefer a stabilized instrument approach from the outer marker to the runway threshold. Along the stabilized approach the aircraft is aligned with the localizer beacon and set up on the proper glideslope. This relatively simple flight path minimizes the demands on the pilot's attention to the instruments. If the current display philosophy were employed to guide the pilot in maintaining a curved path, then constant attention would be required to track the continuously changing flight path, since the cockpit instrumentation in common use reflects only the instantaneous state of the aircraft. Under visual conditions the reaction to curved approach paths is noticeably different since visual curved approach procedures are in common use to achieve low noise approaches and to avoid obstacles in the vicinity of the airport. The obvious difference in the reactions to curved paths is that, under visual conditions, the features indicating the projected ground track enable the pilot to establish his maneuver strategy in advance while, under instrument conditions, he must respond to an immediate indication of the deviation from the nominal profile without reference to the intended flight path in advance of the aircraft. The obvious key word in this discussion is anticipation. If the display indicating guidance information would enable the pilot to anticipate the control actions required to maintain the desired flight path, then the stigma associated with curved approaches might be eliminated.

In this context, the Course Deviation Indicator (CDI) type of display would be totally inadequate, since no predictive information or general orientation is displayed. The flight director type of display is better, since the flight director mechanization includes course angle data and could be configured to provide the necessary anticipation. When combined with an orientation display it could be suitable for both curved and straight segments, either RNAV or MLS. Electronic Cockpit Displays (Attitude Indicators and Horizontal Situation Indicators) have already been shown to be particularly suitable for displaying the intended path during manual and automatically controlled curved approaches.

The last factor common to both RNAV and MLS involves the control of along track position or equivalently the management of time-of-arrival at a given reference point. This concept of time control, commonly referred to as 4D guidance, is primarily intended to serve the anticipated requirement for the scheduling of aircraft along the approach course and thus achieve a more efficient traffic flow in the high density terminal area. The latter control concept involves two distinct operational functions, metering and spacing. Metering occurs as aircraft enter the terminal area and involves the orderly transition of aircraft into the approach pattern. Spacing occurs in the approach pattern and along the approach course as aircraft are maneuvered to achieve an ordered sequence of arrivals at the final approach gate. Since MLS guidance is confined to a 120° sector about the extended runway centerline,

it is very likely that the metering process will occur outside the MLS coverage volume. Therefore, metering should be regarded as an RNAV-related function. Thus the primary impact of MLS on 4D guidance should involve only the spacing concept. Recalling that MLS represents a more accurate source of reference within the framework of RNAV operations, it is apparent that the introduction of MLS should not influence the basic design of a spacing algorithm but only impact the degree of precision with which this function can be performed. Thus MLS implementation with 4D processing capability should ultimately result in a more efficient flow of traffic and a higher runway acceptance rate.

D.5 RNAV/MLS COMPLEMENTARY CAPABILITIES

The concern of this section is the identification of means whereby RNAV could supplement the basic MLS configurations to achieve some of the operational advantages available with the more complex configurations. The lowest category of MLS service involves the implementation of only elevation and azimuth elements to serve the requirements of small community airports. Since no collocated DME is provided with this lowest category MLS, the obvious application of RNAV to this configuration is the addition of range to touchdown information. A waypoint located at the airport would indicate this data and aid in the final approach guidance. Also, the lower capability MLS ground configurations (Cat I and Cat I/II) may not have a back azimuth element for guidance on missed approach. In this respect, RNAV could supplement these configurations by providing the basis for missed approach guidance. Further, the early introduction of RNAV to accomplish this objective would also ease the later transition to MLS missed approach guidance for those implementations including a back azimuth element. Another potential application for RNAV supplementing MLS involves the small angle coverage implementations. MLS with only a 20° azimuth scan would not permit many of the curved approach paths possible with the broader coverage configurations. RNAV system capabilities could thus be applied to realize the flexibility of curved approach paths to intercept the narrow coverage MLS guidance for precise control along the final approach leg.

APPENDIX E

RNAV INTERACTION WITH WAKE VORTEX AVOIDANCE

E.1 INTRODUCTION

Aircraft generating lift create a counter-rotating cylinder of air behind each wing termed wake vortices. Wake vortices are invisible under normal conditions and contain energy that is directly proportional to aircraft weight and inversely proportional to aircraft speed. The higher energy vortices created by heavy large-bodied aircraft can present a hazard to following aircraft especially during landing and takeoff. This problem becomes most acute in the terminal area where the larger number of aircraft on the same flight path increases the probability of an encounter with a vortex and where there is little time for aircraft to recover due to the lower altitudes involved.

In the absence of operational means to detect, track, and/or predict the location and severity of wake vortices, the FAA has maintained safety by increasing IFR separation standards from 3 nmi, which was in common use prior to the introduction of wide-bodied heavy aircraft, to 4, 5 and as much as 6 nm (for a light aircraft following a heavy aircraft with 300,000 pounds gross takeoff weight or larger). This increase in separation standards has reduced airport arrival and departure capacity and poses one of the major obstacles with respect to increasing capacity in congested areas and reducing associated delays. More specifically, the imposition of the 4/5/6 nmi spacing during IFR conditions, and the practices used by pilots during VFR conditions to assure safe separation, has caused better than a 10% loss in runway acceptance rates under IFR conditions and a 10%-20% loss in the VFR rate. This loss in capacity is based on today's mix of aircraft and will get worse as the percentage of large heavy aircraft increases.

Thus, the operational problem addressed by the Wake Vortex Avoidance System Program (WVAS) is the problem of inadequate airport capacity at major hub airports caused by separation standards imposed to provide protection against encounters with high energy wake vortices. The technical problem is the problem of learning more about the characteristics of wake vortices to the degree necessary to reduce separation standards and increase airport capacity.

The basic approach being taken in the WVAS program is to gather data on the characteristics of wake vortices and their relationship to meteorological data while at the same time developing and testing various means of detecting their presence and location. In conjunction with those efforts, studies are also underway to determine how results from prediction and detection techniques can best be combined to provide an operationally useful system. Thus, the program is, for the most part, still in the exploratory development phase although some efforts currently underway, such as studies to establish functional requirements and system specifications, could be considered as being in the early phases of advanced development.

E.2 POTENTIAL RNAV INTERACTIONS

The WVAS is clearly a terminal area system, primarily in the vicinity of the runway. Since the WVAS is essentially a means of detecting wake vortices

and alerting controllers to the required separation, its implementation does not have an impact on RNAV.

There is, however, a subtle RNAV impact on the WVAS. This impact is not adverse in that some of the RNAV characteristics can be beneficially applied to aiding the avoidance of wake vortices. These RNAV characteristics include parallel offsets, delay fans and trombones. Implementation of these particular RNAV-related maneuvers, in the terminal area where wake vortices are a problem, provides the capability to circumvent any potentially threatening trailing vortices shed by preceding aircraft.

Consider for example Figure E.1 where, because of a persistent wake vortex detected by the WVAS, the aircraft separation must be increased from s_1 to s_2. The trailing aircraft can use either a delay fan or trombone as shown in the figure. The problem with the trombone procedure is that the trailing aircraft's path would tend to be downwind from the vortex-generating aircraft. Because of drift, due to the wind, the vortex may move into the path of the trailing aircraft. The delay fan, on the other hand, will not only provide increased separation between the aircraft but also move the trailing aircraft out of the path of trailing vortices (with the exception, of course, of an adverse cross-wind causing the vortices to drift into its path). The delay fan departure angles for increased separations of 1, 2 or 3 nmi are shown as a function of distance-to-go to the turn to baseleg in Figure E.2. With a reasonable warning time (distance-to-go greater than 5 nmi, for example) the departure angle is not significantly severe (less than 15°). Conversely, if a standard fan departure angle (such as 45°) were to be utilized, the distance prior to the turn to baseleg where the fan would be initiated could be modified to accommodate varying required delays. In either case it would appear that delay fans would be a viable means of providing adequate aircraft separation for wake vortex avoidance. Naturally, any such maneuvers (whether RNAV or radar vector) resulting from an unanticipated wake vortex problem would upset the Metering and Spacing function.

For straight-in arrivals a parallel offset could be used to avoid a wake vortex threat. Figure E.3 shows this RNAV technique as applied to straight-in wake vortex avoidance. For effective vortex avoidance the offset must be specified on the upwind side. The parallel offset not only removes the trailing aircraft from the path of the vortex but also provides a delay which increases aircraft separation.

α - delay fan departure angle

$\Delta s = s_2 - s_1$

s_2 - desired separation

s_1 - current separation

d - distance-to-go to baseleg to initiate delay fan maneuver

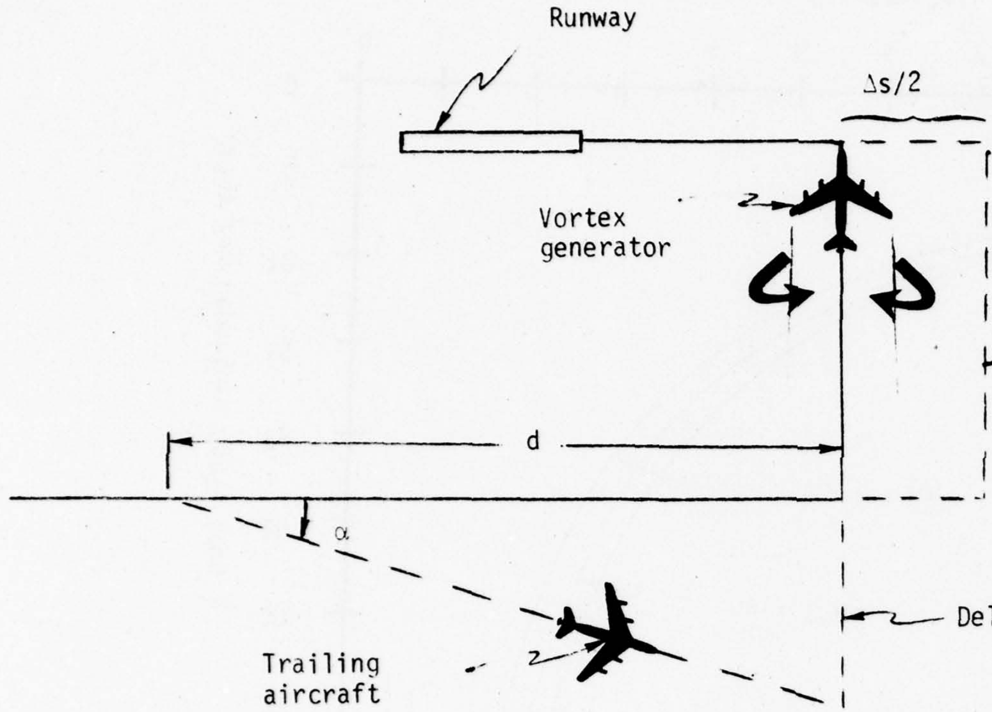


Figure E.1 Delay Fan and Trombone RNAV Maneuvers to Increase Separation for Wake Vortex Avoidance

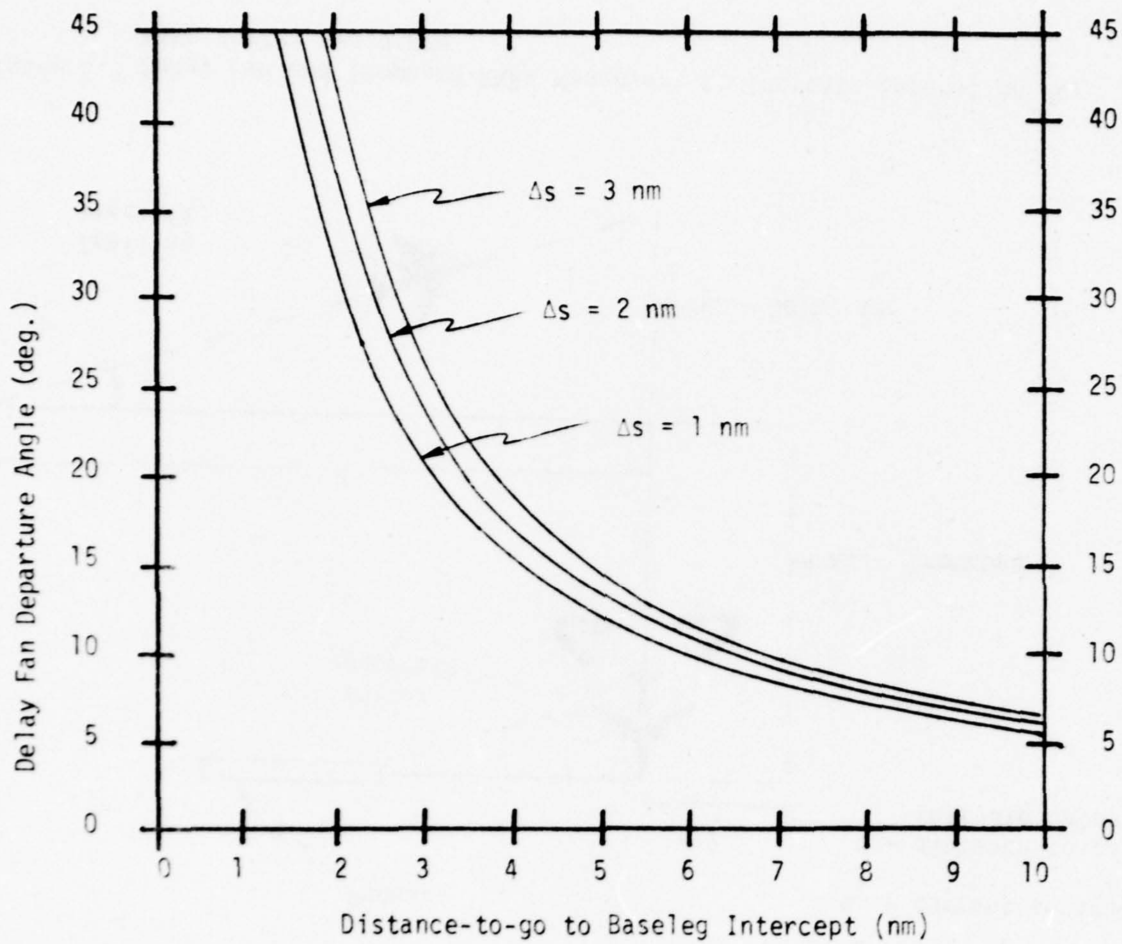


Figure E.2 Delay Fan Departure Angle as a Function of Distance-to-go

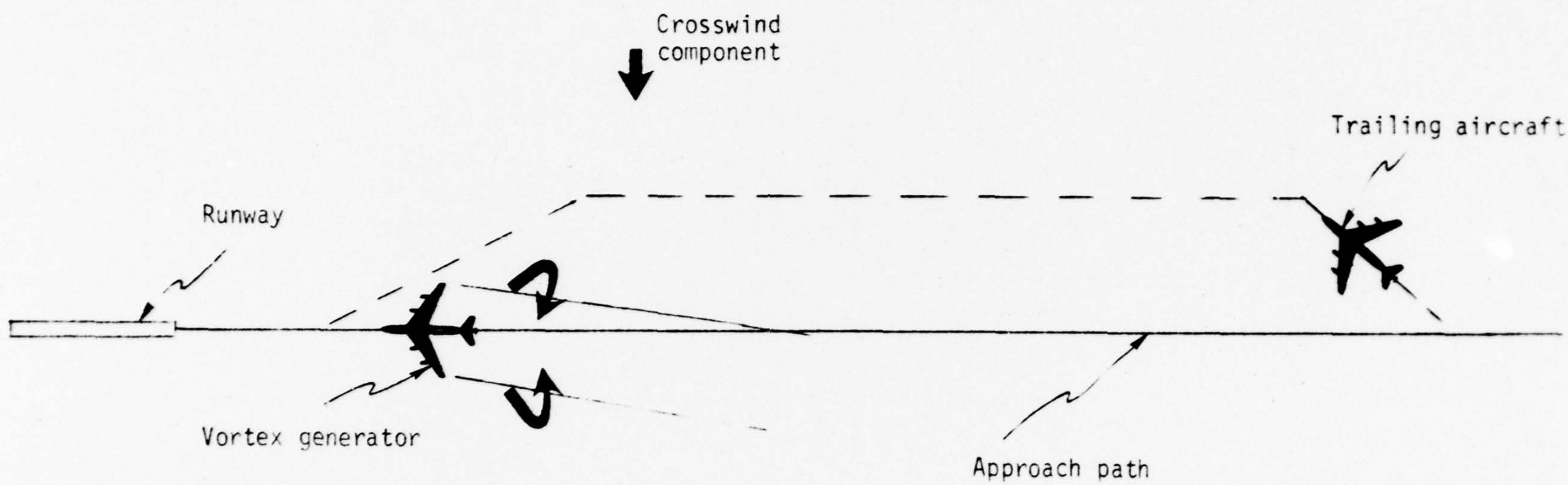


Figure E.3 Parallel Offset for Straight-In Approach Wake Vortex Avoidance

APPENDIX F

AIRLINE DETAILED COST AND BENEFIT TABLES
(Domestic Operations)

Table F.1 Airline RNAV Equipage Costs ($)

	4EWB		3EWB		4ESB		3ESB		2ESB	
	Capital	Maint.	Capital	Maint.	Capital	Maint.	Capital	Maint.	Capital	Maint.
1975	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1976	0.	0.	2397284.	88155.	0.	0.	0.	0.	0.	0.
1977	0.	0.	14912.	88594.	0.	0.	0.	0.	0.	0.
1978	0.	0.	0.	87730.	0.	0.	0.	0.	0.	0.
1979	0.	0.	0.	85563.	0.	0.	0.	0.	0.	0.
1980	0.	0.	0.	82093.	0.	0.	0.	0.	0.	0.
1981	0.	0.	13379.	82486.	0.	0.	0.	0.	0.	0.
1982	11415834.	315760.	34251784.	1084392.	0.	0.	0.	0.	0.	0.
1983	14000749.	747547.	41618427.	2313963.	7644959.	213845.	59282417.	1658249.	27895705.	780299.
1984	16585652.	1235360.	44385648.	3754700.	6958637.	408492.	69548158.	3603652.	26567347.	1523442.
1985	3877360.	1349400.	11391700.	4059750.	6272306.	583942.	79813861.	5836208.	25238971.	2229427.
1986	5823520.	1520680.	26400664.	4880946.	573676.	599488.	2050563.	5893566.	52551.	2230897.
1987	5823520.	1691960.	26400664.	5672142.	279039.	607794.	2050563.	5950925.	0.	2230713.
1988	5823520.	1863240.	26400664.	6463338.	0.	607357.	2050563.	6008283.	0.	2228876.
1989	5823520.	2034520.	26400664.	7254534.	0.	598680.	2050563.	6065642.	0.	2225385.
1990	5823520.	2205800.	26400664.	8045730.	0.	581760.	2050563.	6123000.	0.	2220240.
1991	4606320.	2341280.	34934216.	9190854.	0.	540552.	0.	6024745.	0.	2174304.
1992	4606320.	2476760.	34934216.	10335978.	0.	499344.	0.	5926490.	0.	2128368.
1993	4606320.	2612240.	34934216.	11481102.	0.	458136.	0.	5828234.	0.	2082432.
1994	4606320.	2747720.	34934216.	12626226.	0.	416928.	0.	5729979.	0.	2036496.
1995	4606320.	2883200.	34934216.	13771350.	0.	375720.	0.	5631724.	0.	1990560.
1996	4660040.	3020260.	31901860.	14709640.	0.	329664.	0.	5607594.	0.	1944624.
1997	4660040.	3157320.	31901860.	15647930.	0.	283608.	0.	5583463.	0.	1898688.
1998	4660040.	3294380.	31901860.	16586220.	0.	237552.	0.	5559333.	0.	1852752.
1999	4660040.	3431440.	31901860.	17524510.	0.	191496.	0.	5535202.	0.	1806816.
2000	4660040.	3568500.	31901860.	18462800.	0.	145440.	0.	5511072.	0.	1760880.
1976	79859094.	42726644.	171279460.	17264699.	10148382.	2130231.	100011466.	23934190.	37432819.	8879274.

Table F.2 1976 Present Value Airline Terminal Benefits by Terminal Area (pounds,minutes)

1976	4EWB Fuel	4EWB Time	3EWB Fuel	3EWB Time	4ESB Fuel	4ESB Time	3ESB Fuel	3ESB Time	2ESB Fuel	2ESB Time
EWR	30683633.	81388.	[illegible]	[illegible]	4138114.	15967.	53740541.	398388.	34351750.	351577.
LGA	0.	0.	17443425.	783203.	0.	0.	24422031.	1774705.	115727986.	1258214.
JFK	50360534.	1376721.	32151017.	1371880.	54744674.	250311.	140645965.	1206217.	80793958.	822824.
ORD	35127344.	115100.	52706350.	264664.	2634384.	14877.	42477233.	357005.	19941186.	246306.
MSY	3160481.	4523.	8745015.	17640.	211447.	1090.	11754293.	41675.	9327720.	77132.
DEN	4262322.	25183.	12132218.	149105.	45308.	233.	37024019.	248960.	27044690.	272285.
PHL	5524144.	12057.	10358071.	43245.	464407.	3216.	14988818.	98287.	17451834.	132089.
MIA	24680188.	81578.	50170074.	210872.	2605145.	13694.	41158203.	328301.	16437298.	162390.
SFO	71829274.	231519.	75519185.	356720.	7412624.	41404.	67498814.	625237.	18337992.	225450.
ATL	31043343.	90175.	119426361.	581429.	2121473.	11513.	100853209.	995539.	74550547.	925036.
HOU	20949149.	83261.	38641317.	145134.	3215911.	17277.	38745459.	344300.	35003407.	405574.
CLE	2507432.	17515.	15518800.	74378.	643444.	3499.	14958468.	110920.	16234079.	145381.
DFW	17051444.	44995.	52161938.	248459.	1423603.	9745.	75341469.	663575.	39200169.	448193.
DTW	22218775.	54148.	43435641.	206116.	3434454.	20558.	26882155.	238114.	23024721.	262278.
IAH	4056452.	13953.	12542740.	55314.	543243.	2626.	20414879.	146500.	8872057.	77421.
LAX	107489138.	309597.	108746085.	521252.	8828252.	47670.	57454417.	604461.	19323021.	226129.
PIT	15507442.	29741.	17038513.	74192.	7864.	41.	21484927.	177373.	37830582.	392721.
STL	6270817.	25428.	27263916.	128037.	1155886.	6112.	32213683.	271957.	28990572.	308703.
DCA	0.	0.	19211502.	88332.	0.	0.	30042263.	242528.	18086565.	182585.
BDL	388370.	633.	15247[illegible]3.	4149.	35014.	144.	3081253.	8088.	4049339.	9940.
BUF	0.	0.	2508402.	10001.	0.	0.	6717748.	39701.	8191914.	54625.
CVG	0.	0.	4404534.	18953.	0.	0.	9441294.	59851.	8761828.	64362.
IND	0.	0.	2202476.	7924.	0.	0.	6330690.	29612.	8054809.	38977.
JAX	0.	0.	413224.	-355.	8187.	32.	2724068.	-956.	822117.	-159.
MCI	3059498.	5092.	5213272.	23272.	9514.	50.	24086553.	186682.	11351647.	104732.
SDF	0.	0.	1140943.	3935.	0.	0.	3698820.	15589.	4831755.	21597.
MSP	-101451.	16045.	11556744.	48192.	8451.	43.	14497116.	92574.	10463170.	77117.
MCO	1440424.	4178.	14714513.	69072.	375703.	2022.	15985573.	136014.	3838329.	41958.
PDX	309452.	295.	2447763.	5944.	90042.	407.	7477588.	18992.	2146799.	5606.
SMF	0.	0.	216960.	49.	0.	0.	1642997.	636.	1218953.	607.
TPA	447044.	1445.	4449264.	14186.	234417.	1109.	10656942.	35485.	2845469.	10401.
SEA	15906370.	29856.	19070046.	84061.	1579826.	8279.	18353153.	134620.	4149170.	36968.
MEM	0.	0.	426640.	-2634.	0.	0.	4225036.	-10442.	7212237.	-14131.
PHX	0.	0.	-2381190.	-20836.	-76821.	-640.	674611.	-47115.	2337560.	-42852.
SAT	0.	0.	-540094.	-6072.	-3273.	-36.	1057936.	-26553.	589683.	-7093.
SAN	655226.	1381.	3068253.	9413.	61613.	252.	7856042.	27749.	2109425.	7021.
IAD	-818661.	-3778.	188512.	-3134.	160784.	427.	1409589.	-5713.	1277335.	-3694.
BAL	231724.	73.	1479642.	2394.	30664.	77.	3355573.	4309.	4704518.	4933.
ALB	0.	0.	-131577.	-1217.	0.	0.	164003.	-6158.	1139244.	-15956.
ABQ	0.	0.	-349012.	-3633.	0.	0.	490525.	-22001.	957743.	-15165.
BHM	0.	0.	-163866.	-1610.	0.	0.	290257.	-8134.	1722642.	-21051.
CLT	0.	0.	1620827.	1585.	0.	0.	3352155.	3778.	3742848.	2876.
DAY	0.	0.	265567.	-1625.	0.	0.	1964292.	-4827.	2514867.	-4732.
DSM	0.	0.	-452323.	-3460.	0.	0.	-209246.	-19736.	368126.	-13169.
ELP	0.	0.	-648812.	-5216.	-2493.	-19.	-144176.	-21387.	185827.	-5538.
FLL	-646643.	-2236.	-3728086.	-29883.	-68680.	-568.	127626.	-56492.	766863.	-17359.
TYS	0.	0.	-121891.	-1149.	0.	0.	173053.	-5812.	1129853.	-15044.
LAS	5520909.	5617.	5223872.	17622.	209845.	898.	5817931.	24076.	8980692.	37118.
MKE	0.	0.	1780170.	4806.	0.	0.	4823921.	13674.	5060662.	13251.
BNA	0.	0.	-68579.	-2446.	0.	0.	1243596.	-10079.	2432648.	-14220.
ORF	0.	0.	-155084.	-2206.	0.	0.	667522.	-8519.	1501475.	-11448.
OKC	0.	0.	579538.	33.	10802.	44.	3414811.	793.	1008225.	307.
OMA	0.	0.	-223829.	-3721.	0.	0.	1345299.	-14358.	864848.	-5760.
PVD	0.	0.	-452560.	-3098.	0.	0.	-455902.	-17376.	128689.	-11473.
RDU	0.	0.	-456561.	-3537.	0.	0.	-43343.	-13510.	674560.	-18110.
ROC	0.	0.	87974.	-1362.	0.	0.	1394092.	-5181.	2435146.	-6833.
SLC	0.	0.	-604178.	-5665.	0.	0.	617882.	-22474.	2215845.	-30770.
SYR	0.	0.	-236126.	-2522.	0.	0.	443442.	-9804.	1223984.	-13264.
TUL	0.	0.	-447162.	-7061.	-2785.	-23.	60321.	-28907.	325933.	-7478.
CMH	0.	0.	-661687.	-6845.	0.	0.	871505.	-21019.	1939589.	-21831.

Table F.3 Airline Annual Terminal Area RNAV Benefits (pounds, minutes)

	4EWB		3EWB		4ESB		3ESB		2ESB	
	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time
1976	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1977	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1978	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1979	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1980	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1981	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1982	25047032.	90497.	37206446.	166543.	0.	0.	0.	0.	0.	0.
1983	96784975.	213570.	107032433.	400287.	13577241.	65626.	65676285.	524038.	35051784.	377435.
1984	134644571.	374023.	184487605.	653413.	27102962.	131742.	163304341.	1284579.	97509347.	996975.
1985	155931645.	405185.	211399000.	944420.	36343349.	176200.	262497492.	2034378.	160737224.	1587218.
1986	160594926.	446157.	231523172.	1033631.	35800761.	173573.	275648882.	2104954.	176327764.	1677965.
1987	175225529.	487100.	251122575.	1117775.	34429812.	166414.	288975870.	2147416.	189852661.	1742681.
1988	189856132.	528044.	264457626.	1198181.	32209406.	156176.	295982520.	2167939.	199926519.	1783507.
1989	204486735.	568987.	288467817.	1284007.	29194594.	141648.	304176951.	2224601.	207409505.	1860548.
1990	219117338.	609930.	307448008.	1369833.	25369744.	123206.	311371382.	2281263.	215029962.	1939192.
1991	235742378.	656683.	326285695.	1455300.	20295795.	98565.	319929060.	2350514.	213520994.	1930318.
1992	252367419.	703437.	345123382.	1540767.	15221846.	73924.	328486738.	2419764.	212012027.	1921443.
1993	268992459.	750190.	363961068.	1626234.	10147898.	49282.	337044417.	2489015.	210503059.	1912569.
1994	285617500.	796944.	382798755.	1711701.	5073949.	24641.	345602095.	2558265.	208994092.	1903694.
1995	302242540.	843697.	401636442.	1797168.	0.	0.	354159773.	2627516.	207485124.	1894820.
1996	315534979.	880715.	414405103.	1853496.	0.	0.	360099838.	2668950.	198994304.	1805672.
1997	328827417.	917733.	427173765.	1910624.	0.	0.	366039904.	2710385.	190503485.	1716524.
1998	342119856.	954751.	439942426.	1967352.	0.	0.	371979969.	2751819.	182012665.	1627375.
1999	355412294.	991769.	452711088.	2024080.	0.	0.	377920035.	2793254.	173521846.	1538227.
2000	368704733.	1028787.	465479749.	2080808.	0.	0.	383860100.	2834688.	165031026.	1449079.
1976	957142532.	2665199.	1310064944.	5853527.	97346174.	472386.	1258188979.	9407692.	770806510.	7137556.

Table F.4 Airline Annual Terminal Area RNAV Dollar Benefits -- Low Cost Assumption

	[illegible]		[illegible]		[illegible]		[illegible]		2ESH	
	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40952334.	3244423388.	[illegible]
COSTS	.0375	[illegible]	.0375	[illegible]	.0375	[illegible]	.0375	6.17	.0375	[illegible]
VALUE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	252861025.	121665877.	[illegible]
1976	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1976	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1977	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1978	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1979	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1980	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1981	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1982	1040764.	1205845.	1495017.	1754744.	0.	0.	0.	0.	0.	0.
1983	2879624.	3194279.	3426216.	4971140.	509145.	529602.	2462861.	3257994.	1314442.	2154924.
1984	5649321.	5602865.	7120763.	9216860.	1016361.	1063158.	6123913.	7956702.	3656601.	5702697.
1985	5472438.	6064686.	7916213.	10199822.	1362876.	1421434.	9843656.	12552112.	6027646.	9074887.
1986	6022316.	6683432.	8882119.	11143215.	1342529.	1400734.	10336833.	12987566.	6612291.	9597960.
1987	6570957.	7234758.	9417097.	12071970.	1291118.	1346496.	10836595.	13249557.	7119475.	9964135.
1988	7119605.	7910399.	10105786.	12940355.	1207853.	1260340.	11136845.	13376184.	7497244.	10201660.
1989	7648253.	8523925.	10817543.	13867276.	1094794.	1143099.	11406636.	13725768.	7777656.	10642335.
1990	8216906.	9136751.	11529300.	14794196.	951365.	994272.	11676427.	14075393.	8063624.	11092178.
1991	8840339.	9837111.	12235714.	15711240.	761042.	795420.	11947340.	14502671.	8007037.	11041413.
1992	9463778.	10537486.	12942127.	16640284.	570819.	596567.	12318253.	14929944.	7950451.	10996654.
1993	10087217.	11237846.	13648540.	17563327.	380546.	397706.	12639166.	15357223.	7893865.	10939895.
1994	10710656.	11934221.	14354953.	18486371.	190273.	198853.	12960079.	15784495.	7837278.	10884130.
1995	11334095.	12634581.	15061367.	19409414.	0.	0.	13280991.	16211774.	7780692.	10838370.
1996	11832562.	13173111.	15540191.	20022077.	0.	0.	13503744.	16467422.	7462286.	10328444.
1997	12331628.	13747640.	16019016.	20634739.	0.	0.	13726496.	16723075.	7143881.	9814517.
1998	12829695.	14302170.	16497841.	21247402.	0.	0.	13949249.	16978723.	6825475.	9308585.
1999	13327961.	14856700.	16976666.	21860064.	0.	0.	14172001.	17234377.	6507069.	8798654.
2000	13826427.	15411227.	17455491.	22472726.	0.	0.	14394754.	17490025.	6188663.	8284732.

Table F.5 Airline Annual Terminal Area RNAV Dollar Benefits -- High Cost Assumption

	[illegible] FUEL	[illegible] TIME	[illegible] FUEL	[illegible] TIME	[illegible] FUEL	[illegible] TIME	3ESB FUEL	3ESB TIME	2ESA FUEL	2ESA TIME
TOTAL	43912494[illegible].	1223[illegible]20[illegible].	[illegible]0778560[illegible].	263[illegible]0128.	[illegible]7317.	1[illegible]1.47.	[illegible]5113755652.	40982338.	3244423300.	29665249.
COSTS	.0563	10.16	.0563	21.79	.0563	17.69	.0563	10.20	.0563	9.04
VALUE	247230162.	309134112.	132[illegible]08310.	57[illegible]7008.	1[illegible]332400.	17[illegible]07496.	310424443.	418019848.	182661037.	269757093.
1976	538[illegible]7125.	503[illegible]402.	73[illegible].	127[illegible]814.	[illegible]2842.	[illegible]9056.	70830040.	45953458.	43396407.	64[illegible]257.
1976	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1977	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1978	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1979	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1980	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1981	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1982	1637600.	2427790.	2094388.	3029485.	0.	0.	0.	0.	0.	0.
1983	4323276.	6441271.	5744426.	10025051.	764401.	845919.	3697575.	5385988.	1973415.	3417561.
1984	7580715.	11280534.	10690037.	18587335.	1525497.	1698154.	9194034.	13153706.	5489770.	9032594.
1985	8215954.	12228416.	11884874.	20549642.	2046131.	2271218.	14778609.	20750656.	9049500.	14380195.
1986	9041494.	13458095.	13034755.	22512443.	2015583.	2237356.	15519032.	21470531.	9927253.	15202363.
1987	9865197.	14696936.	14138201.	24345140.	1938398.	2151521.	16269341.	21903643.	10688705.	15784695.
1988	10688900.	15925807.	15172153.	26096342.	1813390.	2013109.	16720116.	22112978.	11255863.	16154573.
1989	11512603.	17160648.	16240738.	27965672.	1643651.	1825343.	17125162.	22690930.	11677155.	16856565.
1990	12336306.	18395489.	17309323.	29834963.	1428317.	1588125.	17530209.	23268883.	12106187.	17569050.
1991	13272298.	19805559.	18369885.	31646434.	1142653.	1270503.	18012006.	23975243.	12021232.	17484681.
1992	14208286.	21215660.	19430446.	33557965.	856990.	952880.	18493803.	24681593.	11936277.	17408274.
1993	15144275.	22625730.	20491008.	35419377.	571327.	635245.	18975601.	25387953.	11851322.	17327875.
1994	16080265.	24035831.	21551570.	37280848.	285663.	317622.	19457398.	26094303.	11766367.	17247468.
1995	17016255.	25445902.	22612132.	39142319.	0.	0.	19939195.	26800663.	11681412.	17167069.
1996	17764619.	26562364.	23331007.	40377855.	0.	0.	20273621.	27223290.	11203379.	16359388.
1997	18512984.	27674827.	24049883.	41613391.	0.	0.	20608047.	27645927.	10725346.	15551707.
1998	19261348.	28793290.	24768759.	42848927.	0.	0.	20942472.	28068554.	10247313.	14744014.
1999	20009712.	29911753.	25487634.	44084462.	0.	0.	21276898.	28491191.	9769280.	13936337.
2000	20758076.	31028216.	26206510.	45319998.	0.	0.	21611324.	28913818.	9291247.	13128656.

Table F.6 Airline Annual Enroute RNAV Benefits (pounds, minutes)

	4EWB		3EWB		4ESB		3ESB		2ESB	
	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time
1982	35354270.	14477.	[illegible]	[illegible]	0.	0.	0.	0.	0.	0.
1983	70436519.	20411.	[illegible]	[illegible]	23587500.	125487.	109470424.	777595.	25557200.	265575.
1984	130446723.	34442.	221149260.	[illegible]	44077409.	234712.	248375577.	1683843.	49897398.	518503.
1985	142484674.	37611.	246483476.	[illegible]	64471105.	342569.	346055364.	2730744.	73020579.	758785.
1986	160574431.	[illegible]	237644379.	[illegible]	71741142.	452006.	389449551.	2763641.	73068724.	759284.
1987	178660944.	471047.	334045201.	1334955.	72125117.	356606.	393043713.	2790538.	73062706.	759223.
1988	196747145.	514731.	[illegible]	1486441.	72072410.	356410.	397437676.	2817435.	73002524.	758594.
1989	214433332.	556410.	427237607.	1669007.	71634550.	351317.	401232038.	2844331.	72888179.	757406.
1990	232419459.	614101.	473441790.	1841033.	69610967.	341389.	405026200.	2871228.	72719670.	755654.
1991	247225347.	651014.	541335010.	2114444.	64679354.	317207.	398526783.	2825154.	71215125.	740024.
1992	261531235.	684537.	601742029.	2377430.	59744041.	293025.	392027366.	2779079.	69710580.	724394.
1993	275437123.	727255.	676229049.	2601388.	54817428.	268844.	385527949.	2733005.	68206035.	708755.
1994	290143011.	754973.	743670009.	2904840.	49887215.	244662.	379028532.	2686931.	66701490.	693121.
1995	304448900.	802691.	811123089.	3148241.	44956502.	220480.	372529115.	2640857.	65196945.	677487.
1996	318421627.	844844.	867381728.	3394158.	39445705.	193454.	370932929.	2629541.	63692401.	661853.
1997	333394353.	870007.	921652366.	3600025.	33934908.	166427.	369336744.	2618226.	62187856.	646219.
1998	347447040.	917165.	974917005.	3815441.	28424111.	139400.	367740558.	2606910.	60683311.	630584.
1999	362134807.	955323.	1033181044.	4031756.	22913314.	112374.	366144373.	2595595.	59178766.	614950.
2000	376412534.	993481.	1087446203.	4247625.	17402517.	85347.	364548187.	2584280.	57674221.	599315.
[illegible]	4791369624.	2531531.	2176553274.	6478300.	254891224.	1250063.	1533206624.	11223342.	290823452.	3022053.

Table F.7 Airline Annual Enroute RNAV Dollar Benefits -- Low Cost Assumption

	[illegible]		[illegible]		4ESA		3ESA		2ESA	
	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6487653304.	45990933.	1157663710.	12029734.
COSTS	.0375	14.[illegible]	.0375	10.80	.0375	4.07	.0375	6.17	.0375	5.72
VALUE	168359360.	177317031.	[illegible]	[illegible]	34451709.	36371151.	243236999.	283764057.	43412389.	68810074.
1976	36717635.	39671304.	[illegible]	[illegible]	4550421.	10088008.	59370249.	69248020.	10905879.	17288183.
1982	1329535.	1400205.	2607271.	2759046.	0.	0.	0.	0.	0.	0.
1983	2960115.	3117623.	5110967.	5744488.	959531.	1012696.	4113391.	4797761.	958395.	1519084.
1984	4891752.	5159041.	8731097.	7379267.	1832920.	1934470.	8939084.	10426331.	1871152.	2965837.
1985	5343325.	5627041.	9633130.	10181763.	2620156.	2765339.	14477077.	16885710.	2738272.	4340255.
1986	6021556.	6341963.	10740064.	12137644.	2692169.	2841334.	14619358.	17051665.	2740077.	4343116.
1987	6649787.	7056284.	12528199.	14093514.	2727192.	2876295.	14761639.	17217619.	2739851.	4342754.
1988	7378018.	7770590.	14275732.	16059345.	2725234.	2876229.	14903920.	17383574.	2737595.	4339181.
1989	8056249.	8484912.	16023266.	18025276.	2686296.	2835120.	15046201.	17549522.	2733307.	4332379.
1990	8734430.	9199231.	17770800.	19991156.	2610378.	2755009.	15188483.	17715477.	2726986.	4322364.
1991	9270951.	9764244.	20100063.	22036427.	2425476.	2559460.	14944754.	17431200.	2670567.	4232937.
1992	9807421.	10329254.	22429326.	25061709.	2240574.	2364712.	14701026.	17146917.	2614147.	4143511.
1993	10343892.	10894280.	25158589.	28526990.	2055672.	2169571.	14457298.	16862641.	2557726.	4054077.
1994	10880363.	11459296.	27487853.	31372272.	1870771.	1974422.	14213570.	16578364.	2501306.	3964652.
1995	11416834.	12024311.	30417116.	34217543.	1685869.	1779274.	13969842.	16294088.	2444885.	3875226.
1996	11959561.	12599918.	32449540.	36548906.	1479214.	1561174.	13909985.	16224268.	2388465.	3785799.
1997	12502244.	13167525.	34461964.	38880270.	1272559.	1343066.	13850128.	16154454.	2332045.	3696367.
1998	13045016.	13739132.	36633388.	41211623.	1065904.	1124958.	13790271.	16084635.	2275624.	3606940.
1999	13587743.	14310737.	38705812.	43542986.	459249.	906458.	13730414.	16014821.	2219204.	3517514.
2000	14130470.	14882345.	40779236.	45874350.	652594.	688750.	13670557.	15945008.	2162783.	3428082.

Table F.8 Airline Annual Enroute RNAV Dollar Benefits -- High Cost Assumption

	[illegible]		[illegible]		[illegible]		[illegible]		2FSH	
	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	914980505.	[illegible]	[illegible]	45990933.	1157663710.	12024734.
COSTS	.0563	40.10	.0563	21.74	.0563	12.59	.0563	10.20	.0563	[illegible]
VALUE	[illegible]	[illegible]	[illegible]	[illegible]	517386602.	[illegible]	365254881.	469107517.	65176467.	104984391.
1976	55125409.	77654035.	[illegible]	[illegible]	14350376.	16113312.	[illegible]	114478088.	16373360.	27374804.
1982	1996075.	2814266.	3614110.	5481226.	0.	0.	0.	0.	0.	0.
1983	4444126.	6274804.	7673175.	11544801.	1440570.	1417553.	6175571.	7931409.	1438870.	2408113.
1984	7344151.	10317854.	12450703.	16514021.	2751824.	3089488.	13420545.	17236399.	2809224.	4697637.
1985	8022112.	11339418.	13861740.	20492849.	3433743.	4417003.	21734918.	27914789.	4111059.	6874592.
1986	9040363.	12768598.	16183371.	24457415.	4041844.	4538369.	21948530.	28189138.	4113769.	6874131.
1987	10058814.	14206778.	18809031.	20421920.	4094424.	4597425.	22162141.	28453488.	4113430.	6878561.
1988	11076864.	15644927.	21432632.	32358446.	4091485.	4594125.	22375752.	28737837.	4110042.	6872894.
1989	12095115.	17083107.	24050263.	35380972.	4033020.	4528470.	22589364.	29012176.	4103604.	6802125.
1990	13113366.	18521286.	26674894.	40315449.	3919047.	4400504.	22802475.	29286526.	4094117.	6846201.
1991	13918787.	19654801.	30477161.	46053452.	3641448.	4048798.	22437058.	28816571.	4009412.	6704617.
1992	14724209.	20794436.	34274428.	51791446.	3363848.	3777092.	22071141.	28346606.	3924705.	6562973.
1993	15529630.	21934011.	38071045.	57529431.	3086249.	3465399.	21705224.	27876651.	3840000.	6421320.
1994	16335052.	23071586.	41868963.	63267415.	2808650.	3153693.	21339306.	27406696.	3755294.	6279674.
1995	17140473.	24209161.	45666230.	69005378.	2531051.	2841987.	20973389.	26936741.	3670588.	6138032.
1996	17955288.	25356006.	48777029.	73700961.	2220793.	2493522.	20883524.	26821318.	3585882.	5996389.
1997	18770102.	26510851.	51889028.	75468545.	1910535.	2145244.	20793659.	26705905.	3501176.	5854735.
1998	19584917.	27661696.	55000427.	83110166.	1600277.	1796966.	20703793.	26590482.	3416470.	5713091.
1999	20399731.	28812542.	58111827.	87811089.	1290020.	1448501.	20613928.	26475069.	3331765.	5571447.
2000	21214546.	29963387.	61223226.	92513272.	979762.	1100123.	20524063.	26359656.	3247059.	5429794.

Table F.9 Airline Annual VNAV Descent Benefits (pounds, minutes)

	4E[illegible]		3E[illegible]		4ESH		3ESH		2ESH	
	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME
1982	1567555.	1049.	7531449.	32256.	0.	0.	0.	0.	0.	0.
1983	3490055.	4125.	15990116.	88944.	5824413.	24361.	38944154.	266096.	31158314.	286607.
1984	5767498.	13427.	25945998.	111131.	11136290.	46572.	94749932.	578271.	60832909.	559565.
1985	6299914.	14066.	28281285.	121047.	15914371.	66575.	137254760.	936525.	89023765.	814876.
1986	7699565.	14524.	33728864.	144445.	16350939.	66405.	135503642.	945730.	89082462.	814414.
1987	7499216.	14396.	39139044.	147843.	18564826.	69295.	139952585.	954934.	89075125.	813944.
1988	8699868.	21251.	44653424.	181390.	18657731.	69245.	141301524.	964138.	89001753.	814673.
1989	9499519.	22113.	50130403.	214714.	16321155.	66250.	142050470.	973342.	88862348.	817391.
1990	10299170.	23975.	55590133.	233135.	15454896.	66327.	143999413.	982546.	88656909.	815581.
1991	10930662.	25447.	61511301.	272029.	14736487.	61629.	141688608.	966780.	86822628.	798624.
1992	11563195.	26920.	71424419.	365922.	13613077.	56930.	139377923.	951013.	84988347.	781757.
1993	12195707.	28392.	73337538.	339815.	12489668.	52232.	137067178.	935246.	83154066.	764884.
1994	12828220.	29865.	87250656.	373708.	11365259.	47534.	134756433.	919479.	81319785.	748012.
1995	13460732.	31337.	95163774.	407601.	10242050.	42836.	132445688.	903712.	79485504.	731139.
1996	14100621.	32827.	101647613.	435372.	8947274.	37565.	131378195.	899840.	77651223.	714267.
1997	14740510.	34317.	108131453.	463144.	7731699.	32334.	131310701.	895968.	75816942.	697394.
1998	15380399.	35806.	114615292.	490915.	6476124.	27083.	130743207.	892096.	73982662.	680522.
1999	16020288.	37296.	121099131.	518686.	5220549.	21833.	130175714.	888224.	72148381.	663649.
2000	16660177.	38786.	127582970.	546458.	3964974.	16582.	129608220.	884351.	70314100.	646777.
1976	43291009.	1066783.	254656839.	1040734.	54074192.	242269.	562879204.	3840675.	354560303.	3261304.

Table F.10 Airline Annual VNAV Descent Dollar Benefits -- Low Cost Assumption

	[illegible]		[illegible]		[illegible]		[illegible]		2ESH	
	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME
TOTAL	1944499891.	462117.	1370410113.	[illegible]	[illegible]	-75634.	2306562955.	15738291.	1411377223.	12982407.
COSTS	.0375	14.98	.0375	10.40	.0375	4.07	.0375	6.17	.0375	5.72
VALUE	7443746.	6922513.	47655370.	56745221.	[illegible]	7056360.	86496096.	97105255.	52926646.	74254304.
1970	1623413.	1504724.	9644631.	11777927.	2177742.	1759453.	21107970.	23696965.	13246011.	14655124.
1982	58733.	54062.	282429.	343346.	0.	0.	0.	0.	0.	0.
1983	130877.	121713.	599629.	739570.	216619.	196755.	1462438.	1641812.	1168437.	1639392.
1984	216281.	201136.	472975.	1260215.	417611.	375436.	3178122.	3567932.	2281234.	3200712.
1985	236247.	214697.	1059798.	1307308.	596976.	537260.	5147051.	5778359.	3338391.	4683971.
1986	266234.	247589.	1264825.	1560222.	613341.	552024.	5197637.	5835154.	3340592.	4687090.
1987	296221.	275482.	1467852.	1813136.	621361.	559211.	5248222.	5891943.	3340317.	4686671.
1988	326208.	303360.	1674678.	2066040.	620915.	558307.	5298807.	5948731.	3337566.	4682810.
1989	356194.	331251.	1879905.	2318954.	612043.	550826.	5349393.	6005520.	3332338.	4675477.
1990	386181.	359146.	2084932.	2571869.	594746.	535259.	5399978.	6062309.	3324634.	4664666.
1991	409901.	381198.	2381674.	2937913.	552618.	497346.	5313325.	5965033.	3255849.	4564154.
1992	433620.	403252.	2678416.	3303958.	510490.	459425.	5226672.	5867750.	3187063.	4471654.
1993	457339.	425312.	2975158.	3670002.	468363.	421512.	5140019.	5770468.	3116277.	4375134.
1994	481058.	447376.	3271900.	4036046.	426235.	383599.	5053366.	5673185.	3049492.	4279629.
1995	504777.	469428.	3568642.	4402091.	384107.	345687.	4966713.	5575903.	2980706.	4182115.
1996	528773.	491748.	3811785.	4702018.	337023.	303311.	4945432.	5552013.	2911921.	4085607.
1997	552769.	514069.	4054929.	5001955.	289939.	260935.	4924151.	5528123.	2843135.	3989094.
1998	576765.	536374.	4298073.	5301842.	242855.	218560.	4902870.	5504232.	2774350.	3892586.
1999	600761.	558694.	4541217.	5601809.	195771.	176192.	4881589.	5480342.	2705564.	3796072.
2000	624757.	581014.	4784361.	5901746.	148687.	133817.	4860308.	5456446.	2636779.	3699564.

Table F.11 Airline Annual VNAV Descent Dollar Benefits -- High Cost Assumption

	4E WB FUEL	4E WB TIME	3E WB FUEL	3E WB TIME	4E SN FUEL	4E SN TIME	3E SN FUEL	3E SN TIME	2E SN FUEL	2E SN TIME
TOTAL	198469891.	462117.	1270410113.	5443076.	201379702.	875534.	2306502555.	15738291.	1411377223.	12942407.
COSTS	.0563	30.16	.0563	21.78	.0563	12.89	.0563	10.20	.0563	9.06
VALUE	11175544.	13937449.	71546609.	110550145.	11788077.	11288922.	129854472.	160530568.	79460536.	117620607.
1976	2437284.	3034015.	14337180.	23750147.	1269577.	3130581.	31040099.	39174885.	19961745.	29548157.
1982	88253.	119054.	424021.	702579.	0.	0.	0.	0.	0.	0.
1983	196490.	248050.	900244.	1491669.	328220.	314271.	2195608.	2714179.	1754213.	2598659.
1984	324710.	404958.	1460760.	2420433.	620473.	600313.	4771421.	5898364.	3424893.	5069659.
1985	354685.	442327.	1591110.	2636404.	896261.	858152.	7727440.	9552555.	5012038.	7419017.
1986	399705.	499484.	1998924.	3146445.	920890.	881740.	7803385.	9646446.	5015343.	7423909.
1987	444728.	554042.	2206737.	3656412.	932870.	893213.	7879331.	9740327.	5014930.	7423293.
1988	449748.	610770.	2514551.	4166514.	932200.	892560.	7955276.	9834208.	5010799.	7417177.
1989	534767.	668928.	2822364.	4676559.	918881.	879420.	8031221.	9928088.	5002950.	7405552.
1990	579787.	723086.	3130178.	5186002.	892912.	854955.	8107167.	10021969.	4991384.	7388433.
1991	615397.	767482.	3575646.	5924792.	829664.	794398.	7977072.	9861156.	4888114.	7235574.
1992	651008.	811907.	4021195.	6662981.	766416.	733828.	7846977.	9700333.	4784844.	7082714.
1993	686618.	856303.	4466703.	7401171.	703168.	673270.	7716882.	9539509.	4681574.	6929854.
1994	722229.	900728.	4912212.	8139360.	639920.	612713.	7586787.	9378686.	4578304.	6776989.
1995	757839.	945124.	5357720.	8877550.	576672.	552156.	7456692.	9217862.	4475034.	6624119.
1996	793865.	990062.	5722761.	9492402.	505944.	484471.	7424742.	9178368.	4371764.	6471254.
1997	829891.	1035001.	6087801.	10087276.	435295.	416785.	7392792.	9138874.	4268494.	6318390.
1998	865916.	1074909.	6452841.	10692129.	364606.	349100.	7360843.	9099379.	4165224.	6165529.
1999	901942.	1124847.	6817881.	11296981.	293917.	281427.	7328893.	9059885.	4061954.	6012660.
2000	937968.	1169786.	7182921.	11901855.	223228.	213742.	7296943.	9020380.	3958684.	5859800.

Table F.12 Airline Annual 4D RNAV Benefits (pounds, minutes)

	4EWB		3EWB		4ESB		3ESB		2ESB	
	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time
1985	[illegible]	615165.	[illegible]	[illegible]	[illegible]	405609.	[illegible]	[illegible]	[illegible]	2454223.
1986	[illegible]	[illegible]	[illegible]	1592301.	[illegible]	[illegible]	[illegible]	[illegible]	163844956.	2467545.
1987	176231713.	718433.	[illegible]	1692320.	[illegible]	305609.	[illegible]	[illegible]	164729478.	2480866.
1988	[illegible]	770667.	[illegible]	1792339.	[illegible]	255711.	[illegible]	[illegible]	165614001.	2494187.
1989	201563402.	821702.	323404003.	1892358.	[illegible]	205813.	[illegible]	[illegible]	166498523.	2507508.
1990	[illegible]	873356.	340497246.	1992377.	[illegible]	155916.	[illegible]	3187270.	167383046.	2520829.
1991	[illegible]	918098.	357397582.	2073713.	[illegible]	124732.	[illegible]	[illegible]	163080209.	2456027.
1992	236189602.	962860.	368297919.	2155049.	[illegible]	93549.	[illegible]	3276704.	158777367.	[illegible]
1993	247169780.	1007622.	382198255.	2236385.	[illegible]	62366.	[illegible]	[illegible]	154474527.	2326424.
1994	[illegible]	1052385.	396098591.	2317721.	9236439.	31183.	[illegible]	[illegible]	[illegible]	[illegible]
1995	269130135.	1097147.	[illegible]	2399057.	4618217.	0.	341980099.	[illegible]	150171686.	2196820.
1996	[illegible]	1141737.	[illegible]	[illegible]	0.	0.	346755330.	3467553.	145868848.	2078891.
1997	[illegible]	1186326.	[illegible]	2525397.	0.	0.	349211578.	[illegible]	[illegible]	1960962.
1998	[illegible]	1230916.	[illegible]	[illegible]	0.	0.	[illegible]	[illegible]	130207856.	1843033.
1999	[illegible]	1275505.	453181652.	2651736.	0.	0.	354124074.	3541241.	122377359.	1725103.
2000	[illegible]	1320095.	[illegible]	2714905.	0.	0.	[illegible]	3565803.	114546863.	1607174.
					0.	0.	359036570.	[illegible]	106716367.	
1976	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1187439709.	11874397.	[illegible]	8537406.

Table F.13 Airline Annual 4D RNAV Dollar Benefits -- Low Cost Assumption

	4E44 FUEL	4E44 TIME	3E44 FUEL	3E44 TIME	4E54 FUEL	4E54 TIME	3E58 FUEL	3E58 TIME	2E54 FUEL	2E54 TIME
TOTAL	3440954816.	15654193.	5409605949.	345747313.	2955765513.	1495789.	53315054480.	53315055.	2375264871.	35772433.
COSTS	.0375	14.98	.0375	10.40	.0375	4.07	.0375	6.17	.0375	5.72
VALUE	144035406.	234554731.	221606473.	373446316.	11084119.	16106017.	199931456.	328953889.	89073370.	204614351.
1976	24747382.	44504221.	45770140.	70616866.	3701154.	5376055.	44529999.	73265024.	21256142.	45533962.
1985	5658751.	9215172.	9563664.	10110646.	2251514.	3271410.	11326541.	18635936.	6111016.	14034154.
1986	6133723.	9944649.	10404060.	11176451.	1974394.	2668433.	11482976.	18893324.	6144186.	14114357.
1987	6606659.	10762126.	10445657.	10277056.	1647274.	2456265.	11639412.	19150711.	6177355.	14194554.
1988	7043658.	11535604.	11460653.	17957261.	1420155.	2063583.	11795948.	19408049.	6210525.	14266750.
1989	7558626.	12304096.	12127650.	20437466.	1143035.	1660911.	11952283.	19665493.	6243695.	14342946.
1990	8073597.	13032573.	12768047.	21517672.	865916.	1258242.	12108719.	19922881.	6276864.	14419142.
1991	8445353.	13753108.	13287909.	22345108.	592733.	1006587.	12287640.	20217204.	6115508.	14044474.
1992	8857110.	14423043.	13811172.	23274529.	519549.	754940.	12466561.	20511647.	5954151.	13677607.
1993	9268867.	15694175.	14132435.	24142958.	346366.	503294.	12645482.	20806036.	5792795.	13307145.
1994	9680623.	15764727.	14453697.	25031347.	173183.	251647.	12824404.	21100419.	5631436.	12936474.
1995	10092380.	16435262.	15174960.	25709816.	0.	0.	13003325.	21394802.	5470082.	12566813.
1996	10502549.	17103220.	15779798.	26592052.	0.	0.	13095434.	21546356.	5176436.	11891257.
1997	10912717.	17771163.	16184636.	27274248.	0.	0.	13187543.	21697903.	4882795.	11214703.
1998	11322886.	18439122.	16589474.	27956513.	0.	0.	13279653.	21849457.	4589151.	10542144.
1999	11733054.	19107065.	16994312.	28638749.	0.	0.	13371762.	22001005.	4295507.	9867584.
2000	12143223.	19775023.	17399150.	29320974.	0.	0.	13463871.	22152558.	4001864.	9193035.

Table F.14 Airline Annual 4D RNAV Dollar Benefits -- High Cost Assumption

	4EAN		3EAN		4ESN		3ESN		2ESN	
	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME
TOTAL	324095461.	1565?193.	[illegible]	345?3713.	295570513.	1445764.	533150?480.	53315055.	237528?871.	3577?433.
COSTS	.0563	40.16	.0563	21.78	.0563	17.89	.0563	10.20	.0563	9.36
VALUE	216245756.	472251101.	432705145.	753124405.	166409956.	257257?20.	300163759.	543813561.	133728820.	324094297.
1976	44720789.	97664082.	70217543.	159947347.	5556840.	6590231.	60052856.	121116849.	31915557.	77344494.
1985	8495671.	18554376.	14154247.	32501902.	3340272.	5225656.	17004913.	30808192.	9174672.	22235205.
1986	9238758.	20116554.	15320597.	34640316.	2944224.	4542472.	17234775.	31233695.	9224471.	22355954.
1987	9921845.	21667939.	16442946.	36458730.	2548175.	3939300.	17474637.	31659199.	9274270.	22474644.
1988	10634933.	23225221.	17245296.	39037143.	2132126.	3296115.	17709499.	32084702.	9324066.	22597333.
1989	11348020.	24782532.	18207645.	41215557.	1716077.	2652430.	17944361.	32510215.	9373867.	22714022.
1990	12061107.	26339814.	19169995.	43393971.	1300028.	2009757.	18179223.	32935718.	9423665.	22834711.
1991	12679291.	27684836.	19952544.	45165469.	1040022.	1607795.	18447844.	33422361.	9181416.	22251605.
1992	13297475.	29034858.	20735173.	46936967.	780017.	1205447.	18716464.	33909043.	8939166.	21664497.
1993	13915659.	30384880.	21517762.	48708465.	520011.	803598.	18985084.	34395716.	8696916.	21077401.
1994	14533843.	31734932.	22300351.	50479963.	260006.	401949.	19253705.	34882378.	8454666.	20490295.
1995	15152027.	33084954.	23082940.	52251461.	0.	0.	19522325.	35369041.	8212416.	19903189.
1996	15767826.	34434784.	23690736.	53627304.	0.	0.	19660612.	35619583.	7771554.	18834752.
1997	16383626.	35774592.	24298533.	55003147.	0.	0.	19794899.	35870116.	7330702.	17766314.
1998	16999426.	37124427.	24906330.	56378987.	0.	0.	19937185.	36120658.	6889845.	16697874.
1999	17615226.	38464231.	25514127.	57754810.	0.	0.	20075472.	36371191.	6448988.	15629433.
2000	18231025.	39814065.	26121924.	59130631.	0.	0.	20213759.	36621733.	6008131.	14560994.